EXPERTS AND NOVICES: DIFFERENCES IN THEIR USE OF MENTAL REPRESENTATION AND METACOGNITION IN ENGINEERING DESIGN

BY

RAYMOND ANTHONY DIXON

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Human Resource Education
with a concentration in Human Resource Development
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2010

Urbana, Illinois

Doctoral Committee:

Professor Scott Johnson, Chair
Professor Ty A. Newell
Associate Professor Peter Kuchinke
Assistant Professor Russell Korte
Professor Rodney Custer, Illinois State University

Abstract

Research shows that mental representation such as analogical reasoning is a fundamental cognitive tool for design problem solving (Daugherty & Mentzer, 2008; Hey, Lensey, Agogino, & Wood, 2008; Lewis, 2008). Not much is known, however, about the way students and professional engineers actively generate and change their mental representation when solving a engineering design problem. There are very few studies that show how different types of mental representations; such as metaphors, propositions, and analogies; interplay with higher order cognitive processes; such as planning, monitoring, and evaluation; as engineering designers navigate their problem and solution spaces. This empirical study investigated the mental representation and metacognitive regulation of student and professional engineers while they solve an engineering design problem. The intent is to gain a deeper insight in the differences that exists in the cognitive process of engineering students and professional engineers.

The research questions guided this study were (a) How do the mental representations (propositions, metaphors, and analogies) of student and professional engineers differ in their problem and solution spaces in terms of their frequency, types, and attributes? (b) How does the metacognitive regulation (planning, monitoring, and evaluation) of student and professional engineers differ in their problem and solution spaces in terms of their frequency and characteristics? and (c) How do the mental representation and metacognitive regulation of students and professional engineers relate to their overall engineering design strategy? Concurrent and retrospective verbal protocols were collected from six mechanical engineering students and four professional

mechanical engineers as they solved an engineering design problem. Their verbalizations were audio recorded, transcribed, and coded.

The conclusions drawn from the data were: the use of mental representations such as propositions, analogies, and metaphors by experts and novice engineering designers in the different mental spaces are important in engineering design. Expert engineering designers use analogies differently in their solution space than do novice engineering designers. Expert engineering designers rely on within-domain analogies, between-domain analogies, heuristics, and formulas differently from novice engineering designers. In engineering design evaluation plays a larger role in the solution space of expert designers while novice designers tend to do more planning in the problem space. Finally, based on the findings recommendations are provided for engineering and technology education curriculum and instruction, engineering practice in industry, and for future research.

Acknowledgments

I would like to express my sincere appreciation and thanks to those individuals who have impacted my life in one way or another and made it possible for me to achieve my academic and professional goals. In particular, I would like to thank my wife Patricia and parents George and Iris for their patience and loving support. Also I am very grateful to my advisor Professor Scott Johnson for his continuous advice and guidance during my doctoral study.

I would not be in the doctoral program at the University of Illinois if it was not for the kind interest of Dr. Rodney Custer, who has followed my professional and academic growth over the years. In addition the various supports – academic, professional, social, and financial – that have been provided by The National Center for Engineering and Technology Education (NCETE) and all the PIs, professors, and fellows that are associated with the center were irreplaceable, and something I will always cherish.

I would also like to thank the faculty and administrative staff of the Human Resource Education Department who have influenced my academic growth and provided various types of assistance over the past three years. Special thanks are extended to my research committee members Professors Ty A. Newell, Peter Kuchinke, Russell Korte, and Rodney Custer for their assistance and suggestions to improve the course of this study. Finally, I like to thank my personal mentor and former teacher Mr. Errol Clarke for all his guidance and advice.

Table of Contents

Chapter 1

The Problem

The rapid evolution of technology and the implication that this has on the engineering profession has not escaped the scrutiny of the National Academy of Engineering (NAE). In a recently released report on the engineers of 2020, the academy emphasized the need for engineers of the future to develop skills in practical ingenuity and creativity, to differentiate them from low wage engineers on the international market (Hey, Agogino, & Wood, 2008). In fact Brophy, Klein, Portmore, and Rogers (2008) admitted that as industries are driven by the rapid development of enabling technologies, industries must become more flexible and adaptive to remain competitive. This flexibility is achieved through a workforce that can utilize newly available technologies and generate innovation of their own. They further suggested that such technological capability in the workforce can only be possible if students entering higher education are prepared differently at the K-12 level, through programs that target the development of technological literacy.

Academic and professional bodies such as the American Society of Engineering Education (ASEE), the National Academy of Engineering (NAE), and the International Technology and Engineering Educators' Association (ITEEA, formerly ITEA), have taken initiatives to standardize the content towards technological literacy. For example, the American Society of Engineering Education provided guidelines for K-12 engineering outreach that focus on hands-on, interdisciplinary, standards-based education emphasizing the social relevance of engineering as a discipline. The National Academy of Engineering publication, *Technically Speaking*, emphasizes the need for all people to achieve technological literacy (Brophy, Klein, Portmore, & Rogers, 2008). Driven by this goal, the Standards for Technological Literacy: Content for the Study of Technology (ITEA, 2000) provide a framework for increasing students' technological literacy at all levels of the K-12 curriculum through the integration of engineering design. In reference to the designing component of the Standards for Technology Literacy, Lewis (2005) argued that it is "the single most important content area set forth in the standards, because it is a concept that situates the subject more completely within the domain of engineering" (p. 37). Consistent with its usage in society, engineering design provides an ideal platform for engineering and technology educators to integrate mathematics, science, and technology concepts for students to solve real-world (ill-structured) problems innovatively and creatively.

The Accreditation Board for Engineering and Technology (ABET) defines engineering design as "the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative) in which the basic sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives, criteria, synthesis, analysis, construction, testing, and evaluation" (Diaz-Herrera, 2001, p. T2D-2). Recent initiatives by the National Center for Engineering and Technology Education (NCETE) to build the capacity in technology education and improve the understanding of the learning and teaching of high school and college students and teachers as they apply engineering design processes to technological problems, has brought to the fore the importance of understanding the mental processes that support expert problem solving in engineering design (NCETE, 2008). If such mental processes can be explained within the framework of cognitive science theories, then an epistemological foundation would be established that can be used to guide the strategies of engineering and technology educators for the professional development of teachers, and for the teaching and learning of engineering design concepts by students.

Studies in cognitive science have improved the understanding of the cognitive processes that are manifested by individuals while solving problems. Cognitive theories help us to understand how incoming information is encoded, stored, retrieved, and how it interacts with the existing knowledge structure of the individual to construct meaning and solve problems. According to Royer (1986), cognitive theories can provide the explanatory framework for approaches that are used in the development of students' understanding and problem solving. Cognitive theories are therefore apposite for explaining the cognitive processes of students and experts when they are engaged in engineering design and problem solving.

Two cognitive constructs that are important when solving engineering design problems are "mental representation" and "metacognitive regulation." When students are given a design problem they must decide what is known, the constraints they have to work with, and what is required by the customer. They then use mental representations such as metaphors, analogies, and propositions to make sense of the problem and develop a solution. As they solve the problem they use executive control processes or metacognitive regulation to plan their strategy, monitor their progress, and evaluate their solution against given or established constraints, criteria, and the client's requirements.

Several studies have investigated the use of mental representations in problem solving. For example, Greca and Moreira (1997) investigated the use of mental models, propositions, and images by college students in solving physics problems involving electrical and magnetic fields. Their findings suggested that college students work mostly with propositions not related to or interpreted according to mental models. Gick and Holyoak (1980) investigated the provision of source analog prior to the tackling of a problem that is superficially different, but conceptually similar. Casakin and Goldschmidt (1999) examined the use of visual analog by expert and novice designers in their work. The results of both studies indicated that people are good at utilizing prior problem and solution information when they are directed to do so, but may not be efficient in detecting analogous information under unprompted conditions. Other studies (Holyoak & Koh, 1987; Keane, 1987) show that past analogies are more readily activated when there are surface similarities in the target problem and the analogy.

The role of metacognition in problem solving has also received considerable research attention, particularly in literacy (reading and comprehension), science, and mathematics. Chan and Moore (2006) examined its influence on the emotional and motivational aspects of learning. Veenman and Verheij (2003) investigated the relation of technical students' general and specific metacognitive skills to their study success. Atman and Bursic (1998) investigated the problem solving strategies of engineering students, and Lawanto (2007) investigated the self-management strategies of students in team-based engineering design.

Statement of the Problem

Research shows that mental representation such as analogical reasoning is a fundamental cognitive tool for design problem solving (Daugherty & Mentzer, 2008;

Hey, Lensey, Agogino, & Wood, 2008; Lewis, 2008). Not much is known, however, about the way students and professional engineers actively generate and use different types of mental representation when solving an engineering design problem. There are very few studies that show how different types of mental representations interplay with higher order cognitive processes; such as planning, monitoring, and evaluation; as engineering designers navigate their problem and solution spaces.

Davidson, Deuser, and Sternberg (1995) explicated four metacognitive processes that are important contributors to problem solving performance across a wide range of domains and types of problems, whether they are well-structured or ill-structured. Their model inextricably linked mental representation and metacognitive regulation (such as planning and evaluation) as stages in the iterative problem solving process, with the former preceding the latter (see Figure 1).

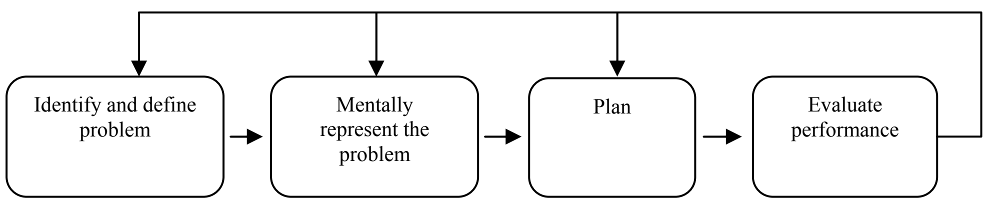


Figure 1. Davidson et al. (1995) metacognitive processes in problem solving.

Maher, Poon, and Boulanger (1996) proposed a model of creative design problem solving based on the co-evolution of the problem and the solution spaces in the design process. As the problem space and solution space co-evolve, information is interchange between the two mental spaces. Dorst and Cross (2001) confirms the accuracy of the Maher et al. model in a protocol study of nine experienced industrial designers whose designs were evaluated on overall quality, creativity, and on a variety of other aspects (see Figure 2).

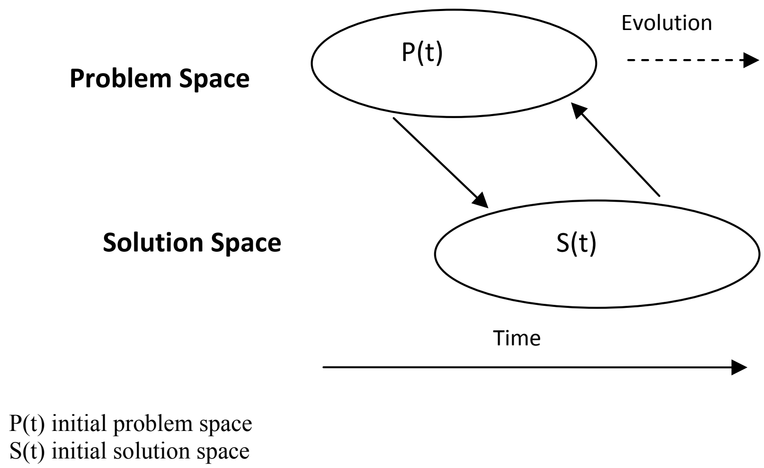


Figure 2. Simplified version of the co-evolution model of Maher et al. (1996).

Superimposing elements of the Davidson et al. model (planning, and evaluation) with the problem and solution spaces of Maher et al. raise questions about how problem solvers actively construct and modify their mental representations within their problem and solution spaces, and their subsequent planning, monitoring, and evaluation strategies. An understanding of how these constructs are used by professional engineers and engineering students when they are solving a specific design problem will add to the limited volume of studies that presently inform the engineering and technology educator about the design cognitive processes of students.

Purpose of the Study

This study investigated the mental representation and metacognitive regulation of student and professional engineers while they solved an engineering design problem. The intent is to gain a deeper insight into the differences that exist in the cognitive process of engineering students and professional engineers as they use mental representations (i.e., propositions, metaphors, and analogies) and metacognitive regulation or executive control processes (i.e., planning, monitoring, and evaluation) to solve an engineering design problem.

Research Questions

This study was guided by the following research questions:

1. How do the mental representations (propositions, metaphors, and analogies) of student and professional engineers differ in their problem and solution spaces in terms of their frequency, types, and attributes?

2. How does the metacognitive regulation (planning, monitoring, and evaluation) of student and professional engineers differ in their problem and solution spaces in terms of their frequency and characteristics?

3. How do the mental representations and metacognitive regulation of students and professional engineers relate to their overall engineering design strategy?

Conceptual Framework Guiding the Study

There are several types of mental representation but for the purpose of this study propositions, metaphors, and analogies were investigated. A proposition refers to the smallest unit of knowledge that one can sensibly judge as true or false. According to Paivio (1990), propositions are the most versatile of representational concepts because they can be used to describe any type of information. They are strings of symbols that correspond to natural language. Unlike language however, propositional representations are assumed to be "completely amodal, abstract, conceptual structures that represent information in the same way regardless of whether the information is experienced verbally, as a spoken or written sentence in whatever language, or nonverbally, as a perceptual scene" (Paivio, 1990, p. 31). The relevance of propositions for engineering design lies in the fact that they can be expressed as general principles, rule of thumb or heuristics; as specific physical laws such as those used in physics; or as a mathematical formula (Greca & Moreira, 1997). Mathematical formulas, scientific principles, and heuristics are important tools that engineers use when performing design activities. These are often used during the analysis phase of the design process, when engineering science formulas are used to ensure structural and functional integrity of the design solution. Analysis also helps to determine the optimal performance of one or more short listed design solutions (Aide, Jenison, Mashaw, & Northrup, 2002).

Metaphors and analogies are important representations used by designers in design problem solving (Casakin & Goldsmith, 1999; Daugherty & Mentzer, 2008; Hey, Linsey, Agogino, &Wood, 2008). Metaphorical reasoning allows one to make conceptual leaps across domains from a source to a target, such that a new situation can be characterized and understood by reference to a similar one. In respect to designing, metaphors are often used in the early stages of the design process to assist the designer to frame the problem. Besides being used descriptively to define the problem and understand the situation, they can also be used prescriptively as a solution generation tool. As stated by Hey and associates (2008), a shower might be seen as a reset because it washes away the rest of the day and start one renewed once they emerge from the shower. In addition, the metaphor, "Shower is a Reset" can be used to "generate other solutions that could support people's feeling of starting anew even to the point of activating the shower with a button" (p. 288).

An analogy can be defined as the "illustration of an idea by means of another idea that is similar or parallel to it in some significant features" (Hey et al., 2008, p. 283). Analogies make possible the solution of a problem in the target domain by superimposing upon it a solution from the base domain (Lewis, 2008). In contrast to metaphors, analogies tend be used more during the generation of solutions and ideation phase of the design, rather than to frame or assist in the understanding the problem. Analogies are generally used to solve functional issues. According to Hey et al., analogies to nature and previous designs are common. For example “a team with the design problem of creating a device to fold laundry may direct analogies to other types of folding devices such as paper folding or metal folding” (p. 288). It is also possible to generate more distance, or between domain analogies, such as dousing a sail or rolling a cigarette for the foregoing design problem. While these comparisons may appear to be metaphors, they are viewed as analogies because they are used to resolve a functional issue by primarily mapping the causal structure between the source product or system in one domain, to the target design problem being solved. Designers also use analogies to support concept selection. Analogies assist the designer to predict the performance of design concepts. In addition, when they are evaluating a set of design concepts they may reference a design they have seen before in their evaluation (Hey et al., 2008).

The framework for this study was conceptualized by integrating the model for creative design, which illustrates the co-evolution of the problem and solution spaces during engineering design problem solving (see Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996), with executive control processes such as planning, monitoring, and evaluation; and mental representations such as proposition, metaphor, and analogy. Whenever engineers are solving design problems their problem and solution spaces co-evolve with an interchange of information between the two mental spaces. This is illustrated by the overlap of the two ellipses in Figure 3. The problem space includes design activities such as defining the problem, searching for information, identifying constraints, and specifying evaluation criteria. The metacognitive regulatory activity that tends to have a more dominant presence in this space is planning. Metaphors are more likely to be generated within the problem space, because they are often used descriptively in the early stages of the design process to frame the problem and better understand the design situation (Hey et al., 2008). Because the designer is trying to understand the problem, it is expected that fewer propositions (mathematics and engineering science principles) and analogies are used by the designer in the problem space.

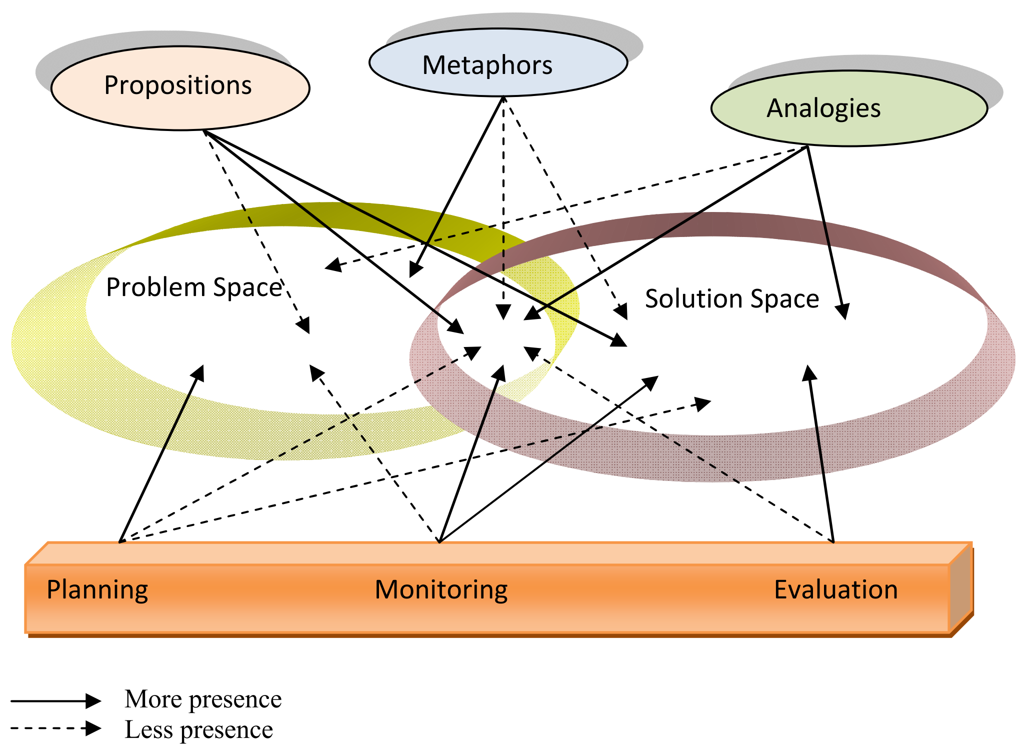


Figure 3. Conceptual model depicting mental representation, metacognitive regulation and the problem and solution spaces.

After a number of possible solutions are generated, then the best of these solutions must be selected. This is carried out primarily through the process of analysis. Potential solutions that are not suitable during the analysis phase, may be discarded, or under certain conditions retained with a redefinition of the problem and a change in the constraints and criteria (Eide, Jenison, Mashaw, & Northup, 2002). Analysis primarily involves the use of heuristics, mathematical formulas, and principles of engineering science—which are propositional in nature—to achieve proper functionality of the component or system. During this process, references are continually made with the criteria and constrains stipulated in the problem. This is also illustrated by the overlap of the two ellipses in Figure 3. The metacognitive regulatory activity that seems to be dominantly featured here is monitoring. It is also expected that analogies and propositions have more presence in this space.

As the designer approaches a solution, more judgmental decisions are made about the merit of the solution. This takes place within the solution space. According to Schraw and Moshman (1995), evaluation includes an individual's control over the internal representations he or she formed, and still needs to form, to understand and solve the problem. It also involves the problem solver appraising whether the solution produced is acceptable to all the parties involved. The designer will ask questions such as: Is the solution within the problem constraints? Is the solution elegant or parsimonious? Could the effects of the solution be optimized? What is the trade-off? If the designer is satisfied with the answers to these appraisals the solution may be adopted. The metacognitive regulatory activities, monitoring and evaluation, will be predominant in the solution space. It is expected that analogy and proposition are the predominant representations within the solution space, since they are primarily used to resolve and refine functional issues of the design (Hey et al., 2008).

Significance of the Study

This study will have significance from a pedagogical content knowledge perspective. It will contribute to the body of research that focuses on understanding how students learn engineering design concepts, and the thought processes behind engineering design problem solving. It is hoped that the differences that exist between an engineering student and professional engineers' design performance will become clearer if a deeper understanding is gained about how they both use and modify their mental representation and regulate their metacognition during when solving an engineering design problem. A better understanding of these cognitive processes may strengthen the link between current practices and the type of instructional interventions that are required to train students to solve problems like experts. Finally, findings from this study may help to identify ways to assess engineering design skills.

Limitations

This study has several limitations. First, the data were obtained from a small sample of engineering students and practicing engineers. Because of the small purposeful sample, attempts to generalize the findings must be limited to the sample. Second, the design task was solved individually and was limited to only a conceptual design solution. This does not reflect the longer periods that may amount to days, weeks, or even months that design teams work to conceptualize, build prototypes, and test design solutions. Third, the verbal protocol delineates complex, non-linear, abstract, cognitive processes to linear verbal expressions, which gives only a partial view into the designer's thinking process. Fourth, there is always the possibility that the process of speaking aloud may interfere in some unknown way with the mental process and problem solving strategy of the participant. Finally, the study highlighted the changes in mental representation and metacognition that take place during the solution of a specific problem, and does not reflect the changes that take place as one develops from a novice to an expert.

Definition of Terms

The following operational definitions were used for the clarity of several specialized terms used throughout this study.

Cognition	Thinking skills and thinking processes used in problem solving and learning (Marzano et al., 1988).
Metacognition	Awareness of one's thinking while performing a specific task, and then using this awareness to control what one is doing (Marzano et al., 1988).
Metacognitive regulation	Higher order metacognitive processes, which include planning, monitoring, and evaluating one's learning or problem solving strategies (Schraw & Moshman, 1995).
Engineering design	A systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints (Dym et al., 2005, p. 103).
Well-structured problem	Problems typically found at the end of a textbook's chapter that requires the application of a finite number of concepts, rules, and principles to constrain a problem situation (Jonassen, 2000).

Ill-structured problem	Problems which are divergent in nature, possess multiple solutions, multiple criteria for evaluation, and require the integration of several content domains (Jonassen, 2000).
Mental representation	Internal representations that are picture-like such as images or language-like such as propositions, which have a mapping relation between the form of the representation and the form in the represented world (Paivio, 1990).
Mental models	A form of mental representation for mechanical-causal domains that affords explanation for these domains. The information in the mental model has an analogical relation with the external world (Brewer, 2003).

Organization of the Dissertation

Discussions in the following chapters are organized as follows: In Chapter 2 the relevant literature that assisted in understanding the concepts of mental representation and metacognitive regulation, and which led to the subsequent conceptual framework described in Chapter 1 are discussed. In Chapter 3, a description is given of the population, sample, and data collection process that were used. In Chapter 4 the findings are presented, followed finally by Chapter 5 which includes the conclusions, discussion, and recommendations.

Chapter 2

Review of the Literature

During the 1960s and 1970s, cognitive learning theory gradually displaced associative learning theory from its dominant position in education. It was theorized that cognitive theories can provide the basis for approaches that are aimed at improving understanding and problem solving (Royer, 1986). Despite this potential opportunity, approximately twenty years later Johnson (1992a) alluded to the lack of interest that technology educators showed in cognitive science-based research. He argued that this disconnect was unfortunate because of the close alignment of many concepts in cognitive science with those in technology education.

Cognition has been defined as the mental process of coming to know. It includes the internal processes of learning, perception, comprehension, thinking, memory, and attention (West, Farmer, & Wolff, 1991). Cognitive science is the study of the "relationships among and the integration of cognitive psychology, biology, anthropology, computer science, linguistics, and philosophy" (Kellogg, 1995, p. 4). Cognitive science explains how incoming information is encoded, stored, and how it interacts with existing knowledge structures to construct meaning. According to Royer (1986), cognitive science is suited for two types of education problems: (a) problems involving understanding and (b) problem solving and thinking.

Studies in cognitive science promise a better understanding of the problem solving processes of both students and experts. Cognitive theories can provide the explanatory framework for approaches that are used in the development of students' understanding and problem solving (Royer, 1986). For example, theories such as Schema and Situated Cognition have refined the teacher's understanding of how the minds of students integrate new information with existing knowledge structures to interpret new situations; how students transfer knowledge learned in class to solve real world problems; and how students' problem solving abilities can be improved. Knowledge from these theories has influenced the pedagogical strategies used by teachers in their instruction. Two cognitive theories that are important in engineering design and problem solving are Mental Representation and Metacognitive Regulation.

Mental Representation

The proper mental representation of a problem is fundamental for the selection of effective solution strategies. Specifically, mental representations have three advantages in problem solving. First, a good representation allows the problem solver to organize blocks of planned moves or strategies as a single "chunk" of memory. Second, it allows the problem solver to organize the conditions and rules of a problem to determine whether certain steps are allowed, or are productive. The third advantage is the problem solver is able to foresee potential obstacles and keep track of where he or she is in terms of reaching a solution (Davidson, Deuser, & Sternberg, 1995).

The content and features of a mental representation are influenced by the domain specific knowledge of the problem solver. For example, experts' mental representations tend to be influenced by domain specific abstract principles, while novices' representations tend to be based on the concrete surface features of the problem. Novices also spend less time than experts in representing the problem, and they are also less able than experts to add new evidence to their representations (Lesgold, 1988). As the problem solver gains a more complete understanding of the givens, goals, and constraints in a problem, or as they find information that was previously overlooked, their representation of the problem may modify or change.

Two systems are theorized to exist within a person's cognitive structure: (a) the symbolic reasoning system and (b) the associative reasoning system. In the symbolic reasoning system, reasoning is applied to real world problems through rule laden symbolic representations such as "propositions." In the associative reasoning system, problems are reasoned through association or similarities using representations such as metaphors and analogies (Daugherty & Mentzer, 2008).

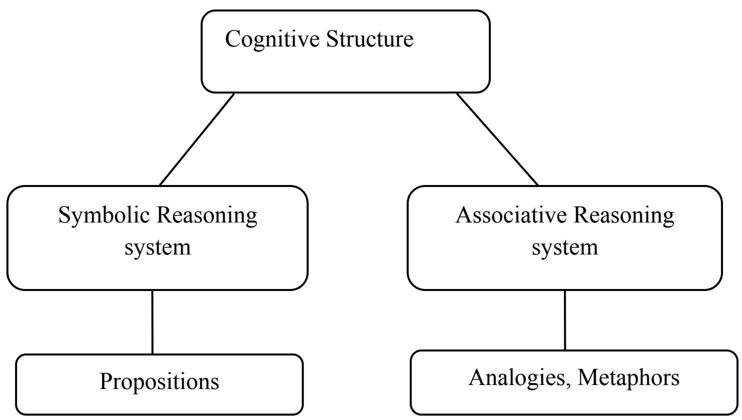


Figure 4. Symbolic and Associative reasoning system.

Propositions. A proposition refers to the smallest unit of knowledge that one can sensibly judge as true or false. It is an assertion that can be understood and evaluated. For example the expression "the lever is to the left of the switch" or "the shaft surface is corrugated" can be evaluated as true or false statements. According to Kellogg (1995), a proposition is an abstract representation of the meaning conveyed by language in words, phrases, sentences, paragraphs, whole speeches, and documents. It provides an abstract and elemental representation of the meaning of verbal information.

Paivio (1990) purported that “propositions are like natural-language statements that correspond semantically to external objects and events” (p. 31). However, unlike language, propositional representations are assumed to be abstract or amodal structures that represent information in the same way. This is the case regardless of whether the information is experienced verbally as a spoken or written sentence, or nonverbally as a perceptual scene. Proposition is the most versatile of representational concepts because it can be used to describe any kind of information.

Paivio (1990) implied that propositions are not limited to simple logic or factual statements, but can be in the form of scientific symbols and notations. Propositions can be expressed as general principles, heuristics or rule of thumb, as specific physical laws, or as mathematical formulas (Greca & Moreira, 1997). For example, science formulas such as $KE = \frac{1}{2} mv^2$ and $F= mv^2/r$ etc. are viewed as scientific propositions. Designers use various mathematical and engineering science formulas when performing analysis to solve engineering design problems.

Analogy and metaphor. An analogy can be defined as the “illustration of an idea by means of another idea that is similar or parallel to it in some significant features” (Hey, Linsey, Agogino, & Wood, 2008, p. 283). Gentner and Markman (1997) explained that the fundamental property of an analogy is its relational and structural similarity. For example, the jaws of a clamping device can be compared with an analogy to the jaws of a pipe wrench, or the design of a car door handle can be compared to the design of other door handles. Hey et al. (2008) referred to how the fuel cell bipolar plate design was generated from an analogy to a leaf. They mentioned that the critical functions of the bipolar plate for current generation are distributing, guiding, and dispersing a fluid over its surface. Because leaves have the same functional attributes, drawing an analogy from the leaf to the fuel cell allows the engineer to make use of Nature’s experience.

A metaphor can be defined as a “figurative expression which interprets a thing or action through an implied comparison with something else” (Hey et al., 2008, p. 283). A metaphor spans the spectrum from relational similarity to appearance similarity. Hey and associates concluded that an important variation between analogies and metaphors, especially in designing, are the elements that are mapped between domains, and how they are used in the design process. An analogy tends to have more surface and domain similarities with the target object. It is principally used to solve functional issues by mapping the casual structure from the source product in one domain, to the target design problem.

Metaphorical and analogical reasoning in design can be further differentiated in the following ways. Metaphorical reasoning allows one to make conceptual leaps across domains, from a source to a target, so that a new situation can be characterized and understood by reference to a familiar one. They make possible connections among unlike entities through principles of association (Lewis, 2005). For example, a cafeteria when seen as an Oasis for its visitors inspires unique solutions that are consistent with this imagery. Metaphors frame and assist designers in defining the design problem. They are mostly used to map the user’s understanding, activities, and reactions to a product. They also help make sense of the physical attributes of a customer’s needs. Metaphors’ exceptional communication ability provides meaning to a design situation (Hey et al., 2008).

In contrast, analogies make possible the solution of a problem in the target domain, by superimposing upon it a solution from the base domain. Designers also use analogies to support concept selection, because the analogies assist the designer to predict the performance of design concepts. In addition, when they are evaluating a set of design concepts they may reference a design they have seen before in their evaluation.

Studies on analogies indicated that people are good at utilizing prior problem and solution information when they are directed to do so, but may not be efficient in detecting analogous information under unprompted conditions (Gick & Holyoak, 1980: Needham & Begg, 1991). In a think-aloud protocol study of 61 architectural designers (17 experienced designers with at least seven years of experience; 23 advanced architecture students in their third, fourth, or fifth year of undergraduate studies; and 21 beginning architecture students in their first or second year of undergraduate studies) similar results to Gick and Holyoak were obtained. Casakin and Goldschmidt (1999) assigned two experimental conditions: (a) Solving design problems with visual displays provided and with the explicit requirement to use analogies and (b) Solving design problems with the visual displays provided but without explicit requirement to use analogies. Their results indicated that the use of visual analogy improves the quality of design for expert and novice designers, but is particularly significant in the case of novice designers.

In another study, Ball, Omerod, and Morley (2004) conducted think-aloud protocols of expert engineers with a minimum of 7 years of academic and commercial design experience, and novices who were master's engineering students with limited design experience. Each participant received an identical brief that related to the design of an automated car-rental facility. This brief was designed "to be complex, multifaceted, and ill-defined in the traditional sense of a prototypical design problem but tractable enough to be tackled to a satisfactory level by designers with only a few years of design experience" (p. 502). They found that experts displayed greater evidence of analogical reasoning than do novices, irrespective of whether such analogizing is "schema-driven" or "case-driven." Schema-driven analogizing involves "the recognition-primed application of abstract experiential knowledge that could afford a design solution to a familiar problem type" while case-driven analogizing entails "the invocation of a concrete prior design problem whose solution elements could be mapped onto the current problem." They also found that the expert designers showed more evidence of schema-driven analogizing than case-driven analogizing, while the novice designers showed more evidence of case-driven analogizing than schema-driven analogizing.

Christensen and Schunn (2007) studied the relationship of analogical distance to analogical function and pre-inventive structures such as prototypes or sketches. They used the vivo methodology; a methodology that allows researchers to study expert thinking and reasoning "online" in the real world; to study 19 expert engineering designers in an international company known for their creativity. They explained that analogical distance may be either large or short during analogical transfer. Large distant or between-domain analogies exist when there are little surface similarities between the source and target, while local or within-domain analogies exist when there are greater superficial similarities between source and target. An example of a between-domain analogy is trying to develop a door handle for the auto industry and comparing the door handle with a telephone or an oyster. A within-domain or local analogy is comparing the door handle to various car door handle designs. They found that the reference to exemplars (in the form of prototypes) significantly reduced the number of between-domain analogies between source and target, as compared with using sketches or no external representational system. They also found that problem-identifying analogies were mainly within-domain, explanatory analogies were mainly between-domain, and problem-solving analogies were a mixture of within- and between-domain analogies.

A closer look at both Ball et al. (2004) and Christensen and Schunn (2007) studies reveal similarities between case-driven and within-domain analogies, and between schema-driven and between-domain analogies. Both case-driven and within-domain analogies are identified by superficial similarities. While schema-driven and between-domain analogies are primarily identified by their underlying conceptual similarities.

Metacognition

The concept of metacognition was first introduced in the 1970s (Veeman, van Hout-Walters, & Afflerblach, 2006). Flavell (1978) coined the term "metacognition" referring to it as knowledge and cognition about cognitive phenomena. Since the seventies, a plethora of studies in various disciplines have focused on this concept.

Definitions of metacognition. A few notable definitions by early researchers in cognition and some later researchers are worth mentioning. Flavell (1978) and Brown (1978) defined metacognition as knowledge and cognition about cognitive phenomena, or the monitoring of one's own memory, comprehension, and other cognitive processes. Kellogg (1995) referred to metacognition as cognition about cognition or thinking about thinking. He saw it as a central feature to human consciousness that enables one "to be aware of, monitor, and control mental processes" (p. 211). Dunslosky and Thiede (1998) viewed metacognition as higher-order mental processes involved in learning such as creating learning plans, using appropriate skills and strategies to solve a problem, making estimates of performance, and calibrating the extent of learning. Several conceptual models are used to explain the metacognition phenomenon.

Flavell's model of metacognition. Flavell (1979) apportioned metacognition into two main constructs that interact with a person's goals (or tasks) and actions (or strategies). These constructs are metacognitive knowledge and metacognitive experience. Metacognitive knowledge refers to stored declarative knowledge about people as cognitive creatures and their diverse tasks, goals, actions, and experiences. This knowledge can lead one to select, evaluate, revise, and abandon cognitive tasks, goals, and strategies. On the other hand, metacognitive experience refers to any conscious cognitive or affective experiences that accompany or pertain to any intellectual event or phenomena. So, metacognitive experience involves using metacognitive strategies and these strategies may become the source for adding to, deleting from, or revising one's metacognitive knowledge.

Paris and Wingrad's model of metacognition. Paris and Wingrad (1990) sorted metacognition into two significant features—cognitive self-appraisal and cognitive self-management (see Figure 4). Cognitive self-appraisal encompasses learners' personal judgment about their ability to meet a cognitive goal. Such judgment is influenced by factors such as the intrinsic goal orientation of students; their perception of their self-efficacy or their ability and confidence to perform the task; their evaluation of the task value; and the learning belief or student's certainty that the outcome is contingent on his or her own efforts. Cognitive self-management refers to the student's ability to plan, monitor, and evaluate their learning.

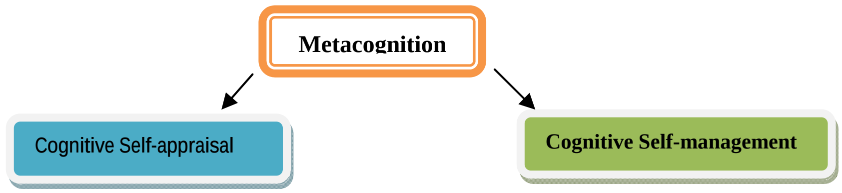


Figure 5. Paris and Wingrad's model of metacognition

Metacognitive regulation. Schraw and Moshman (1995) made a distinction between metacognitive knowledge and metacognitive control processes—the latter also referred to as metacognitive regulation or executive control. Metacognitive knowledge exists in three forms: (a) declarative (b) procedural and (c) conditional. Declarative knowledge includes knowledge about oneself as a learner and about the factors that influence one's learning. For example, adults tend to have more knowledge about the cognitive processes associated with their memory (Garner, 1987). Procedural knowledge refers to knowledge about the execution of procedural skills. According to Glaser and Chi (1988), individuals who displayed a high level of procedural skills, such as experts, sequenced their strategy and varied the quality of their strategy automatically. Conditional knowledge refers to knowing when and why to apply various cognitive processes. Older children and adults appear better able than younger children to selectively allocate their attention, based on the conditional demands of a task (Schraw & Moshman, 1995).

Meijer, Veenman, and van Hout-Walters (2006), in a synthesis of the literature on metacognition, related that several studies identified some commonalities of higher order (executive control) cognition. For example, like Flavell, Schraw and Moshman (1995) subdivided metacognitive control processes into planning, monitoring, and evaluation. Pintrich and DeGroot (1990) viewed metacognition to consist of planning, monitoring, cognitive strategies, and awareness. O'Neil and Abedi (1996) also agreed with the aforementioned researchers' perception of metacognition; viewing it to consist of planning, monitoring, and evaluation.

Metacognition and problem solving. The role of metacognition in problem solving has also received considerable research attention, particularly in literacy (reading and comprehension), science, and mathematics. In a three year longitudinal study of years 5-7 and 7-9 students, Chan and Moore (2006) examined the influence of metacognition on the emotional and motivational aspects of learning. They found that the enhanced beliefs of students in the personal control that they have over their success and their greater use of strategic knowledge are likely to lead to higher achievement. Veenman and Verheij (2003) investigated the relation of technical students' general and specific metacognitive skills to their study success. A verbal protocol analysis of 16 technical university students was conducted while they performed two tasks. Their findings support the generality of metacognitive skills across tasks and domains. Their findings also suggested that metacognitive skillfulness contributed to learning results (partly) independent of students' intellectual skills. Lawanto (2007) investigated the self-management strategies of students in team-based engineering design. His participants included three disciplines of engineering students (Electrical-Computer, Mechanical, and Computer Science) who participated in their senior design classes. In total there were 60 teams. His findings indicated that cognitive self-appraisal and self-management are closely related. Students' metacognitive abilities do not relate to the level of difficulty of the design project, and the metacognitive skills employed by students across the three engineering disciplines were the same during the design task.

Davidson, Deuser, and Sternberg (1995) delineated the metacognitive processes that are important for problem-solving across a wide range of domains into four stages: (a) identifying and defining the problem (b) mentally representing the problem (c) planning how to proceed and (d) evaluating what you know about your performance (see Figure 1). A description of each process will be provided with the exception of "mentally representing the problem," which was explicated earlier.

Identifying and defining the problem. This metacognitive skill recognizes and defines the givens and goals of the problem. According to Newell and Simon (1972), the first step in problem definition is to encode the critical elements of the problem situation. Encoding is storing features of the problem in the working memory and retrieving from stored memory information that is relevant to these features. After encoding, the problem solver must determine what is known and what is being asked for in the problem (Davidson, Deuser, & Sternberg, 1995). In other words, the problem statement is mapped onto prior knowledge and a personal interpretation of the problem is constructed. It should be noted that ill-structured problems are often more difficult to define because there are no well-defined givens and goal states. After the problem is identified and defined, a mental representation of the problem is then created.

Planning. According to Davidson et al. (1995), planning entails dividing the problem into sub-problems and devising the sequence for how the sub-problems should be completed. Individuals are more likely to engage in planning when solving ill-structured problems because the situation is often novel and complex, so planning or structuring brings clarity to ones intended actions. The plan is often revised or modified as the problem solver confronts obstacles during the solution process. This is consistent with Jonassen's (1997) view that ill-structured problems possess multiple solutions, because they can have multiple representations and multiple problem spaces. Different problem representations can lead to alternative solutions, with each solution having its own set of constraints.

The problem solver needs to gather evidence to support or reject the various alternative solutions. Planning requires time and cognitive resources, but in the long run it can improve the efficiency of solving a problem. Indeed, planning for ill-structured problems can be challenging, because on the surface the problem may seem routine and so induces the problem solver to become fixated on only one solution path. Research shows that individuals with less expertise in solving a particular type of problem spend less time in global "up front" planning, and relatively more time in attempting a solution than do experts across age levels and from different areas of expertise (Davidson et al., 1995).

Evaluating one's performance. Davidson, Deuser, and Sternberg indicated that monitoring as a metacognitive process is concomitant with evaluation. Some researchers however, treat both as separate processes (see Flavell, 1979; Kincannon et al., 1999; Schraw & Moshman, 1995; Veenman, van Hout-Wolters, & Afflerbach, 2006). For the purpose of this study, both will be treated as a separate process.

*Monitoring***.** Schraw and Moshman (1995) referred to monitoring as one's awareness of comprehension and task performance, and the ability to engage in periodic self-testing while learning or solving a problem. They reported that groups of students that were trained in both problem-solving and monitoring solved more difficult problems and took less time to do so. According to Kitchener (1983), “ill-structured problem solving should engage meta-metacognitive processes whereby individuals monitor the epistemic nature of the problems they are solving and the true value of the alternative solutions, not just the comprehension monitoring of metacognitive strategies that serve well-structured problem-solving” (p. 82).

The monitoring process relies on a variety of memories such as idiosyncratic memories, emotional memories, problem related memories, and abstract rules. Ill-structured problems, such as engineering design, are contextually driven. The problem solver, however, must apply abstract rules or propositions similar to those used when solving well-structured problems in knowledge domains such as mathematics and physics in order to achieve an optimal solution. Monitoring is a complex process that causes the problem solver or learner to reflect on the meaning of what they know and have been taught; reflect on what others believe; and develop arguments to support their emergent representation of the problem space.

Evaluation. Evaluation is the appraisal of the products and regulatory processes of learning and problem solving. According to Schraw and Moshman (1995), this typically includes re-evaluating one’s goals and conclusions. The representations used by problem solvers are referenced as they appraise their performance. Davidson et al. (1995) purported that evaluation includes control over the internal representations formed, and still need to be formed, for understanding and solving the problem. Jonassen (1997) further added that evaluating one’s performance after the implementation of a solution includes the designer appraising: (a) whether the solution produced is acceptable to all the parties involved (b) whether the solution is within the problem constraints articulated (c) whether the solution was elegant or parsimonious and (d) whether the effects of the solution could be optimized.

Engineering Design Problem Solving

Among the problems that are encountered in practice, design problems are viewed as some of the most complex and ill-structured. Design problems often have ambiguous specifications of goals, no determined solution path, and the need to integrate multiple knowledge domains (Jonassen, 2000). In addition, there are many degrees of freedom in the problem statement, multiple solutions, and output in the form of artifacts and systems that must function independently of the designer (Goel & Pirolli, 1989).

Engineering design. Engineering design can be defined as a "systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve the clients' objectives or users' needs, while satisfying a specified set of constraints" (Dym et al., 2005, p.103). When solving engineering design problems, the problem space includes activities such as defining the problem, identifying constraints, specifying evaluation criteria, and gathering information about various solutions. The generation of solutions and the execution of problem solving strategies define the solution space. Specifically, this includes activities such as making decisions about a solution, performing analysis, optimizing the selected solution, and determining specifications. Figure 6 illustrates the stages of the design process and the mental spaces in which they are likely to take place. The overlapping ellipses represent the co-evolving of both the problem and solution spaces. Within this overlap, an interchange of information takes place between the two spaces (Maher et al., 1996). For example, in reference to this co-evolution and interchange of information, Dorst and Cross (2001) observed designers "redesign the problem, and check whether this fits in with earlier solution-ideas. Then they modify the fledgling–solution they had" (p. 434).

Figure 6 illustrates that analysis and alternative solutions are likely to takes place where the solution and problem spaces overlap. Analysis allows engineers to work with relevant equations and relationships that are necessary for an accurate understanding of the design problem.

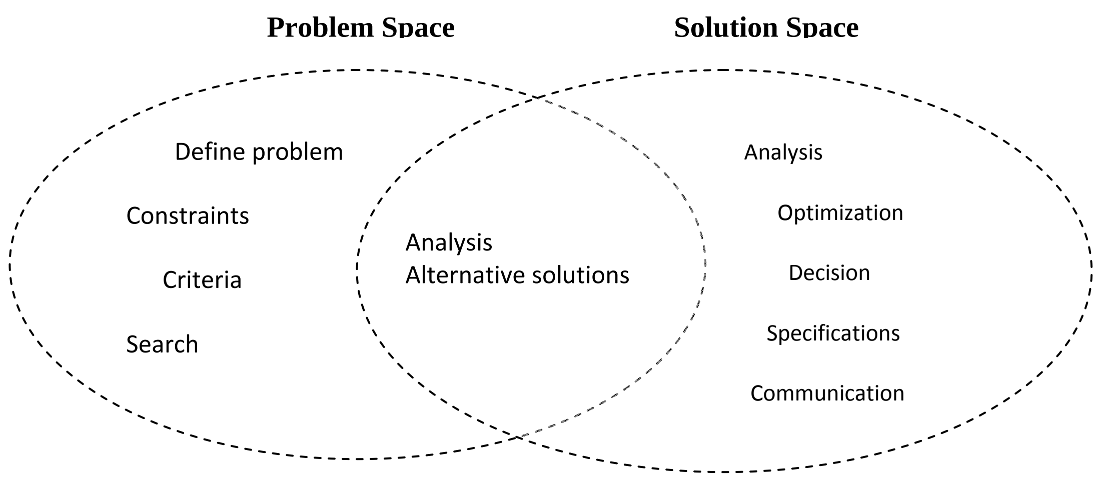


Figure 6. Engineering design process and mental spaces.

An in-depth analysis is done to all the possible solutions to determine which best satisfies the criteria and constraints of the problem. Proper analysis allows the best of the alternative solutions to be short-listed (Eide, Jenison, Mashaw, & Northup, 2002).

Design problem solving of experts and novices. It is the goal of every teacher to assist their students to attain reasonable expertise in knowledge and problem solving. However, to effectively guide students to expert performance teachers need to understand the cognitive processes of their students and also those of experts. They also should be able to use effective teaching strategies to reduce the gap between their students' performance and those of experts. A significant amount of research on the nature of expertise, in various knowledge domains, has been done. In a synthesis of most of these studies, Bedard and Chi (1992) differentiated the knowledge structure, problem representations, and problem solving strategies of experts and novices. Some of their descriptions, along with a summary of findings in design expertise by Cross (2004), are presented below.

Knowledge structure. Experts have a large amount of domain specific knowledge in comparison to novices. More crucially, their knowledge is organized so that it is easily accessible, functional, and efficient. This might be explained by the fact that experts spend many hours in deliberate practice and strive to go beyond their current abilities. Such practice results in highly structured schemas defined by an abundance of procedural knowledge, with conditions for application. Their knowledge is cross-referenced with a rich network of concepts. For example, in a study of electronic technicians' ability to recall symbolic drawings, Egan and Schwartz (1979) suggested that the memory of expert technicians is organized around "conceptual chunks" of information, causing them to remember portions of the drawing as groups of information (e.g. amplifier circuits, tuner circuits). In contrast, novices' schemas can be characterized as having declarative knowledge about the physical configuration of a problem, without abstract solution methods and fewer, weaker, links among concepts. Therefore, novices tend to sort problems on the basis of literal surface features, while experts tend to sort problems on the basis of the principles or theoretical concepts involved. This would account for Ball, Omerod, and Morley (2004) findings in a concurrent protocol of 8 expert and 8 novice industrial engineers. The experts demonstrated more spontaneous use of schema-driven analogies (analogies based on abstract solution structures) than case-driven analogies (analogies based on surface features). In contrast, the novice designers demonstrated more case-driven analogies than schema-driven analogies.

Problem representation. The generation of quality mental representations improves performance and decreases the experienced task difficulty when solving a problem (Romer, Leinert, & Sachse, 2000). According to Bedard and Chi (1992), experts are more efficient and superior in classifying problems according to relevant features. They are also efficient in their inference about additional aspects of the problem. Experts represent problems according to their conceptual features, and spend a considerable amount of time developing their representation by adding domain specific and general constraints. In contrast, novices' representations are largely based on literal features and they may attempt to solve problems directly without properly defining them.

Because of their experience, experts have more sophisticated causal mental models that are governed by concepts from several related domains. Mental models are "transient dynamic representations of a particular unique situation" (Practor & Dutta, 1995, p. 210). Causal mental models appear to be most beneficial in technical and design problem solving because they allow experienced technicians to mentally operate a system and predict its behavior. They also facilitate the remembering of system components (Johnson & Satchwell, 1993).

Christiaan and Dorst (1992) as well as Atman and Bursic (1998), noted the difficulty novices had while identifying pertinent information in a problem. In protocol studies of engineering students, they found that novice students (students with limited or no design experience) became stuck on information gathering and defining the problem, rather than on generating solutions. In contrast, senior designing students processed information quicker and gave the impression of consciously building an image of the problem.

Problem solving strategies. The strategies that experts use in solving problems differ in many ways from the strategies used by novices. Nonetheless, there are similarities in some of their strategies. Experts and novices tend to use the same general problem solving strategies such as means-ends analysis, generate-and-test, or analogical reasoning. However, in means-ends analysis experts tend to use a forward-driven strategy, while novices use a backward-driven strategy. In the forward-driven strategy the problem solver works from the problem givens and use applicable operators to reach their goal. In the backward driven strategy the problem solver works backward from the goal to the problem givens (Bedard & Chi, 1992; Bereiter & Scardamalia, 1987). According to Bedard and Chi, this preferred approach by experts stems from knowing enough about the problem domain so as to automatically recognize the problem type. On the other hand, when the forgoing is not the case, both experts and novices use the backward-driven strategy.

In a case study of three exceptional designers, two of which involved retrospective interviews and one a protocol study, Cross (2002) noted that all three designers either explicitly or implicitly rely upon engineering science principles (first principles) in both the origination of their concepts and in the detailed development of concepts. He also observed that all three designers appeared to explore the problem space from a particular perspective (e.g., personal or usability), in order to frame the problem in a way that stimulates and pre-structures the emergence of design concepts. Finally, he observed that creative design arises especially when there is a conflict to be resolved between the designer's high level problem goals and the client's criteria for an acceptable solution.

In another study of nine experienced industrial designers by Kruger and Cross (2001), the protocol data collected showed four different strategies employed by the designers. They were problem driven, information driven, solution driven, and knowledge driven design strategies. The different strategies appeared not to be related to overall solution quality in any straight forward manner.

Atman and Bursic (1998) used verbal protocol analysis to determine the design strategies of undergrad engineering students. In an in-depth analysis of two of the engineering students, they found two different approaches used in solving a playground design problem. Subject One spent a greater proportion of time scoping the problem, while Subject Two spent a greater proportion of time in detailed calculation. They also addressed different issues. Subject Two concentrated on materials and material costs and spent more time doing calculations, while Subject One spent more time addressing constraints and a wider variety of issues such as safety and handicapped accessibility.

Expertise in design. In a review of various types of design expertise, Cross (2004) provided a comprehensive body of empirical information describing the characteristics of expert mechanical engineers, industrial engineers, and architects when solving design problems. His review illustrates the superior use of metacognitive strategies, mental representations, and inter-domain knowledge by experts. It also illustrates the difference that exists between experts' and novices' performance in engineering design problem solving. The characteristics were as follows:

- Experienced designers use more generative reasoning in contrast to less experienced designers who use more deductive reasoning.
- Expert designers select features of the problem space to which they chose to attend (naming) and identify areas of the solution space which they chose to explore (framing). In addition, expert architects approach to problem solving was characterized by strong paradigms or guiding themes, while novices had weaker guiding themes.
- Expert designers and advance student designers exhibited fixation to their principal solution concept for as long as possible, making 'patches' or slight modification rather than discarding for alternatives.
- Whenever the cognitive cost for following a particular strategy becomes too high, expert designers will abandon or deviate from a principled, structured approach.
- Expert designers use non-linear strategies in problem solving. Often an interleaving of problem specification with solution development, drifting through partial solution development, and jumping into exploring suddenly recognized partial solution. They also use a mixture of breadth-first and depth-first approaches. Novices tend to follow a more linear depth-first approach.
- Unlike novices, experts have the ability to alternate rapidly between activity modes (examine-drawing-thinking) in rapid succession to make novel decisions.
- Outstanding designers seem to have the ability to work along parallel lines of thought. This means they maintain openness, even ambiguity about features and aspects of the design at different levels of detail, and consider these levels simultaneously as the design proceeds.
- Outstanding design expertise is fuel by personal commitment.
- Outstanding designers rely implicitly or explicitly on first principles in origination and development of concepts.
- Experts' creative solutions arise when there is a conflict to be resolved between the expert's own high level problem goal (their personal commitment) and the established criteria for acceptable solution by a client or other requirements.
- The superior performance of experts is domain specific and does not transfer across domains (Cross, 2004, p. 427-441).

A Method for Understanding Expert's Cognitive Processes

A protocol is a "description of activities ordered in time, in which a subject engages while performing a task" (Hayes, 1989, p.51). Verbal Protocol Analysis (VPA), also known as "think-aloud" protocols, are often collected during (concurrent protocols) and after (reflective or retrospective protocols) problem solving episodes, to obtain a record of the knowledge used by the problem solver, and the succession of mental states through which he or she passes while working on the problem (Proctor & Dutta, 1995). When conducting a verbal protocol, the participants are asked to say aloud everything they think, while performing the task, no matter how trivial it seems. The obvious benefits of this type of analysis include the relative ease with which participants typically verbalize their thoughts, and the potential for insight into their cognitive processes. Once the verbal protocols are collected by audio and/or video, they are transcribed, segmented into codable units of subject statements, coded according to a coding scheme, and analyzed to answer specific research questions.

VPA emerged in the 1920s as a method for exploring problem solving in psychological research. The use of tape recorders in the 1940s provided a more accurate documentation of verbal reports. By the 1970s the use of video recording technology generated additional opportunities for describing nonverbal activities. Think-aloud protocol has been used extensively in reading and comprehension studies (Donndelinger, 2005). Atman and Bursic (1998) argued that concurrent report is a valid method that can be used to collect data about someone's thinking process. However, some have expressed concern that think-aloud protocols may distort or interfere with the mental processes that we seek to observe (Proctor & Dutta, 1995). Others contend that when protocols are collected properly it does not distort or interfere with the participant's thinking and performance, because information is being collected from the short term memory, while subjects are prompted to "keep talking" with minimal interference from the experimenter(see Christensen & Yasar, 2007; Ericsson & Simon, 1993).

Verbal protocol analysis has been used by several researchers in engineering design to understand the cognitive process of experts and novice designers. Descriptions of some of these studies which are of relevance to this research were given earlier (see Atman & Bursic, 1998; Ball, Ormerod, & Morley, 2004; Christensen & Schunn, 2007; Christiaan & Dorst, 1992; Cross, 2002; Dorst & Cross, 2001). A more recent study by Cardella, Atman, Turns, and Adams (2008) investigated the changes in individual engineering students design process over their course and how these changes might prepare them to become global engineers. Verbal protocol analysis was used to gain insight of the design behavior of engineering students as well as faculty members. A total of 61 students from various engineering disciplines participated. Some of their findings revealed that the more experienced designers (seniors) tend to spend more time in design activities such as evaluating design alternatives, making design decisions, and communicating design decisions. Senior engineering students had more complete design solutions. Their solutions also had additional mechanical and technical features. Finally, they found that differences in "the structure of the task may affect students' use of 'analytical skills', their 'holistic, multidisciplinary thinking', their tendency to 'exhibit creativity', the extent to which they exhibit 'high ethical standards and a strong sense of professionalism' and their use of 'the principles of business management'" (p. 257).

Atman et al. (2007) conducted an in-depth study of engineering design processes. A verbal protocol of nineteen experts from a variety of engineering disciplines was done while each designed a playground in a lab setting. Measures of their design processes and solution quality were compared to pre-existing data from 26 freshmen and 24 seniors. Their findings showed that experts spent significantly more time on the task overall and in each stage of the engineering design. The experts worked with almost twice as many objects than the novices, and while they spend longer time solving the problem and ended up with higher total number of transitions, the difference was not statistically significant. Finally, the major differences between advance engineers and students were problem scoping and information gathering and they proposed that students would benefit from instruction designed to develop these skills.

Summary

This literature review provided a detailed discussion of two cognitive constructs that are relevant to engineering and technology education; mental representation and metacognition. The roles that mental representation such as proposition, metaphor, and analogy plays in general problem-solving and more specifically engineering design were discussed. The literature shows that mathematical and scientific propositions, metaphors and analogies are important mental representations in design problem solving. Propositions are used primarily during analysis and metaphors help the designer to frame and define the problem and to also make sense of the physical attributes of a customer's needs. Designers primarily use analogy to support concept selection, predict the performance of design concepts, and resolve functional issues. The process of solving design problems involves the metacognitive regulatory activities of planning, mentally representing the problem, monitoring progress, and evaluating their solutions. These executive control processes are concomitant with the evolution of the problem and solution spaces. In addition, the problem and solution spaces co-evolve with information exchanging between both spaces. The review revealed differences and some similarities in the knowledge structure, problem representation, and the problem solving strategy of expert and novice designers. Finally, the successful use of verbal protocol analysis, a technique which originated in the field of psychology to better understand mental strategies, makes it a useful methodology for engineering and technology educators to use in research that investigate the cognitive processes and strategies used in engineering design problem solving.

Chapter 3

Method

This study investigated the differences in the mental representation and metacognitive regulation of students and practicing engineers during engineering design problem solving. The intent was to gain a deeper insight in the differences that exist in the cognitive process of engineering students and professional engineers as they use mental representations (i.e., propositions, metaphors, and analogies) and metacognitive regulation (i.e., planning, monitoring, and evaluation) to solve engineering design problems. The research questions were:

1. How do the mental representations (propositions, metaphors, and analogies) of student and professional engineers differ in their problem and solution spaces in terms of their frequency, types, and attributes?

2. How does the metacognitive regulation (planning, monitoring, and evaluation) of student and professional engineers differ in their problem and solution spaces in terms of their frequency and characteristics?

3. How do the mental representation and metacognitive regulation of students and professional engineers relate to their overall engineering design strategy?

This study reflected the qualitative research tradition of cognitive psychology. According to Gall, Gall, and Borg (2007), cognitive psychology studies the mental structure used by individuals in different situations. It focuses on the inner experience of people in general, of particular types of people (e.g., experts as compared to novices in a field of enquiry), of individual's as they interact with each other, or as they solve problems. Educational researchers, who work within the tradition of cognitive psychology, have studied phenomena such as teacher thinking, student learning process, and learning motivations.

Research Design

A comparative case study of engineering students and practicing engineers was conducted. A purposeful, maximum variation sampling process was used. In purposeful sampling the goal is to “select cases that are likely to be information-rich with respect to the purpose of the study.” Maximum variation sampling, a special type of purposeful sampling, entails the “selecting of cases that illustrate the range of variation in the phenomena to be studied” (Gall, Gall, & Borg 2007, p. 178, 182). Comparing engineering students with professional engineers, who have accumulated years of practice in the field, provided sufficient variation in propositional and analogical reasoning so that differences and similarities can be identified.

Population. The target populations were mechanical engineering students from the College of Engineering, University of Illinois at Urbana-Champaign and professional mechanical engineers practicing in the state of Illinois. Mechanical engineers were selected because verbal protocal studies require that the researcher adequately understands whatever process is used by the participants (Proctor & Dutta, 1995). In this case the researcher is knowledgeble of the mechanical engineering design process. Purposeful samples of mechanical engineering students and professional engineers were selected. The student participants were juniors and seniors who have completed one or more courses that have enginering design elements in its content. A letter requesting permission to ask students to participate in this study was sent to the Associate Dean of Undergrad Studies in the Department of Mechanical Science and Engineering. After permission was granted, two emails informing the students about the study were sent to mechanical engineering students, by two instructors who teach design courses. Six students agreed to participate (3 seniors and 3 Juniors). A consent form that explained the nature of the study, the benefits of the study to the field of engineering and technology education and also to the participant, was given to each student. The form also assured each student of the low risk nature of the study and of their confidentiality and anonymity. The students signed their signature and the dated the form. Professional engineers who are considered to be experts by their peers in mechanical engineering were recommended by a professor emeritus of mechanical engineering. Each professional engineer possessed at least an undergraduate degree in mechanical engineering. The number of years they have worked as engineers ranged from 7 to 40 years. Except for one professonal engineer, their individual number of years in the profesion exceeded the minimum 10 years of experience it generally takes to achieve expertise in a particular domain (Phye, 1986). A total of 4 professional engineers participated. A consent form similar to that which was given to the engineerng students, was also given to each professional engineer to read, sign, and date before attempting the design task.

The design task. Each participant was given the same engineering design problem to find a conceptual solution. The solution was limited to sketches and/or design notes. Before administration, the design task was vetted by an Engineering Technology professor with over 20 years teaching experience, and a Mechanical Engineering professor with over 10 years experience as a manufacturing consultant, and over 3 years experience teaching manufacturing principles. This was to ensure the design task was of sufficient ill-structure, and of the appropriate difficulty level to engage the students and professional engineers. The main recommendations were (a) minor grammatical corrections were required to remove ambiguity in some section of the question and (b) the scope was too large for the allotted time and the question needed to be rephrased to require the participants to modify an existing product. The design task was modified according to these recommendations. After the design task was modified, it was then checked by a professor who teaches the senior design project course. His view was the problem was suitable for students who were presently doing their senior design project. The task was pilot tested with a mechanical engineer with over 20 years experience. He was given the design task in Figure 7 along with pencil and paper. He did not require a practice session and he was asked to speak-aloud as he conceptualized a solution for the problem. He was audio recorded as he solved the problem. The design task proved to be of sufficient rigor—the engineer took approximately 40 minutes to complete his conceptual solution.

DESIGN TASK

Instruction

The objective of this engineering design activity is to understand the cognitive process of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 Hr

The context

Fonthill is a hilly terrain in the District of St. Mary with narrow tracks and virtually non-existent roads. This area also experiences high amounts of rainfall yearly. There are several communities like Fonthill on this mountainous tropical island. Because of the very poor state of the roads the most frequent mode of transportation are motorcycles. Motorcycles are used to take residents to and from work, market, and school. While the residents see this system of transportation as essential, the government has serious concerns about the safety of the riders and their passengers. The government therefore secured a loan to purchase a fleet of motorcycles that are specially built to handle these rugged terrains. These motorcycles will be leased as taxis to specially trained riders.

Figure 7. The engineering design task (continued)

The design problem

The Honda CRF230 shown on the next page is a cross between a dirt bike and a street bike. Modify the Honda CRF230 so that it is robust enough to handle repeated journeys through these mountainous terrains that are prone to a lot of rainfall annually. The average cost of a new car in this country is about US$25000.00 and the government expects that the cost of this motorcycle will not exceed one third this cost. The motor cycle must also:

- Be equipped with more cargo carrying capacity and at the same time make the rear seating (pillion) more comfortable.
- Have an improved rack or a holding system for carrying packages, books, or a reasonable amount of groceries on the motorcycle. The rack must be non-metallic but of sufficient sturdiness to withstand a rugged terrain, occasional brushing against rocks, and a lot of rainfall.
- Be capable of enough horsepower to climb sections of mountains with slopes of 30 degrees, carrying the rider and the pillion passenger.
- Have a device to prevent the theft of helmets from the motorcycle.

Honda CRF230M .

Figure 7. The engineering design task.

Procedure

The design task was administered at a time and place convenient for each participant. Pencils, erasers, and sketchpads were provided along with the instruction for the design task. Each participant was allowed approximately one hour to complete the design solution. A $25 gift card was given to each participant.

Data collection. Data was collected primarily through Verbal Protocol Analysis. The first stage of data collection, referred to as concurrent protocol, was carried out while the design problem was being solved. The second stage of data collection, referred to as retrospective protocol, was performed after the problem was solved. The third stage of the data collection was an analysis of the sketches and notes of each designer.

Concurrent protocol. Each participant had the choice of doing a practice session of about five minutes, thinking aloud as they solve a simple mathematical problem to prepare them for the study. After they were comfortable with thinking aloud, then the task was administered. The participants were encouraged to speak aloud whatever they were thinking as they solved the problem. As they think-aloud they were audio recorded. If the participants stop talking, they were prompted or reminded to continue to speak aloud what they were thinking.

Retrospective protocol. After each participant completed the engineering design problem, an interview was conducted to clarify sections of the protocol and to allow the participant to explain representations used and metacognitive strategies applied. Like the concurrent protocol, the interviews were audio recorded. Their response to the interview questions served as a supplementary data source to the concurrent protocols. A general interview guide format was used. According to Gall, Gall, and Borg (2007), with the general interview format, no set of standardized questions are written in advance because the order in which the topics are explored and the wordings of the questions are not predetermined. Examples of some questions that were asked are:

> "What imagery first came to your mind and influenced how you went about solving this question?"
> "Could you explain where you got the idea of a perforated rack?"
> "In what way does the analogy of your chair at home help to improve your solution?"

Data Analysis

After each participant completed their design task, the audio recordings of their concurrent and retrospective protocols were transcribed. The transcribed protocols were then segmented into think-aloud utterances, divided into sentences, and coded. The quality of the sketches was not evaluated since the objective of the study was to examine the mental processes of the engineering students and professional engineers while solving the design task. The sketches and notes however, acted as a reference to clarify some sections in the protocols.

Segmenting of protocols. The purpose of segmenting is to break the transcribed verbal protocol text into units (or segments) that can be coded with a pre-defined coding scheme. The segmenting took place in two stages. In the first stage, larger units of analysis called *think-aloud utterances* were identified and segmented from each other. Think-aloud utterances comprise those words spoken aloud by a participant that were followed by some period of silence (Hartman, 1995). These periods of silence or pausing were of five or more seconds. A total 270 utterances were segmented (150 for the professional engineers and 120 for the engineering students). The think-aloud utterances were further segmented into sentences.

Coding. Codes were provided for thirteen predefined constructs (see Table 1). The three constructs that described the participant's metal representation were *proposition*, *analogy,* and *metaphor*. The constructs that described the participants' metacognitive regulation were *planning*, *monitoring,* and *evaluation*. The mental spaces that defined the problem solving episode were *problem space, solution space, and overlapping space*. Each utterance was coded for the mental representation used, the type of metacognitive regulation employed, and the mental spaces in which these constructs occurred. The transcripts were also coded for within-domain and between-domain analogies and for propositions that were either heuristics or formulas.

Table 1

Constructs, Codes and Their Meaning

Construct	Code	Meaning
Mental Representations		
Propositions	Prp	Mathematical and engineering science formula and rule of thumb used for example in analysis e.g. $F = mv^2/r$; *'lowering the fame will lower the center of mass.'*
Heuristic	Prp-Heu	Rule of thumb e.g. *'lowering the fame will lower the center of mass.'*
Formula	Prp-For	Math or science formula e.g. $F = ma$.
Analogies	Anl	Comparing an idea with another idea that is similar in structural and relational features e.g. *comparing the surface texture of a leaf with the surface texture of a plate in a battery.*
Within-domain analogy	Anl-Wd	Analogies that are from the same domain e.g. *Comparing two types of scissors; comparing two types of bicycles. Using a device with two pliers like shell crackers opposing each other (Hey et al., 2008)*
Between-domain analogy	Anl-Bd	Analogies drawn between two ideas from different domains but are used to resolve functional issues in a design e.g. *Comparing the shape of car to the shape of a fish for aerodynamic reasons. Comparing a device to remove blood clots to a plumbing or piping system (Hey et al., 2008).*
Metaphors	Mta	Allows one to make conceptual leaps across domains from a source to a target so that a new situation can be characterized and understood by reference to a familiar one. They help to provide meaning to a design situation e.g. *viewing a gas station design problem as an oasis. Understanding a design situation by comparing an electronic book delivery design to a restaurant metaphor (Hey et al., 2008).*
Metacognitive Regulation		
Planning	Pla	Dividing the problem into sub-problems and strategizing how to reach a solution e.g. *Gathering data, prioritizing the requirements in design brief, identifying constraints.*
Monitoring	Mon	Engaging in periodic self-testing and assessment of the quality of design as one progress to a solution e.g. *Performing analysis; testing the accuracy of a formula, calculation, or sketch for the accuracy of a clamping force.*
Evaluation	Eva	Appraising or judging whether the solution of a design meets constraints, costs, and all the demands of the stakeholder; judging quality of two or more design e.g. *Appraising whether one component is designed with the cheapest material that can guarantee the required strength and quality required by the customers.*

(continued)

Table 1 (continued)

Construct	Code	Meaning
Mental Spaces		
Problem space	Prb-sp	Includes design activities such as gathering information, defining the problem, identifying constraints, specifying evaluation criteria, and initially searching alternative solutions.
Solution space	Sol-sp	Includes activities such as developing a solution, sketching, drawing, deciding between two alternatives, optimizing a selected solution, and determining specifications.
Overlapping spaces	Prb-Sol	The mental space where information is interchange between problem and solution spaces. Involves consulting the design brief to make verification then returning to the solution or start a new solution. Activities include analysis and the selection of alternative solutions.

Interrater Reliability. Reliability coding was conducted by having one additional person code seven pages of the first transcript (Miles & Huberman, 1994). A reliability kappa coefficient of 0.76 was calculated for the first coding. All disagreements between coders were resolved through discussion. The constructs 'case-driven' and 'schema-driven' analogies were removed because of their similarity to within-domain and between-domain analogies respectively. A second coding was done by both coders on the same number of pages of another transcript and a reliability kappa coefficient of 0.9 was calculated.

To answer Research Questions 1 and 2, within case data were analyzed using matrix tables (see Appendices). A "matrix is essentially the 'crossing' of two lists, set up as rows and columns" (Miles & Huberman, 1994, p. 93). The rows represented each mental representation (proposition, analogy, and metaphor) and metacognitive regulation (planning, monitoring, and evaluation). The columns were the problem, overlapping, and solution spaces. According to Miles and Huberman, this type of display is especially useful for exploratory eyeballing and understanding the flow, location, and connection of events. The total frequency of mental representations (proposition, metaphor, and analogy) and metacognitive regulation (planning, monitoring, and evaluation) for the engineering students and professional engineers, were then placed in Meta-matrix tables (see Appendices B & D). Frequency histograms were then generated to show the percentage distribution of mental representation and metacognitive regulation of the engineering students and professional engineers in each of the mental spaces. In addition, pie-charts were used to illustrate the percentage of within-domain and between-domain analogies and the percentage of heuristics and formulas used by both groups. A table was also used to compare the planning, monitoring, and evaluation (metacognitive regulation) characteristics of the engineering students and professional engineers.

To answer Research Question 3, segment distribution charts were constructed for each participant to show how their mental representations are distributed over time and in relationship to their planning, monitoring, and evaluation. Finally, network diagrams were constructed to compare the cognitive strategy used by participants in each group, who demonstrated significant difference in the duration that they took to solve the design problem. A causal network is a display of the most important independent and dependent variables in a field of study (shown in a box) and of the relationships among them (shown by arrows). These relationships are directional rather than solely correlational and it is assumed that some factors may exert an influence on others (Miles & Huberman, 1994).

Chapter 4

Results

The results of this study are based on data collected from verbal protocols of six mechanical engineering students and four professional mechanical engineers who participated in solving an engineering design task. Two main variables—mental representation (proposition, metaphor, and analogy) and metacognitive regulation (planning, monitoring, and evaluation)—and how they are used in the mental spaces (problem, overlapping, and solution) of the engineering students and professional engineers, and their relationship to the engineering design strategy used by both the engineering students and the professional engineers are reported.

Results are presented by giving an overview of the engineering design experience of each participant to help readers understand their background. Pseudonyms are assigned to the participants. Each research question is then answered using descriptive statistics such as histograms, pie charts; segmented distribution charts, network diagrams, matrix tables; and verbatim reports from the protocols.

Participant's Engineering Design Experience

Three of the six mechanical engineering students were seniors and three were juniors. The combined years of mechanical engineering experience of the four professional engineers amounted to 112 years. Table 2 gives an overview of the engineering design experience, the gender, and academic level of the mechanical engineering students and professional engineers.

Table 2

Participant's Gender, Academic Level, and Design Experience

Engineering Students	Gender	Level	Design Experience
*Don	Male	Senior	Completed several design courses and senior design project. He was a part of a group that designed a tractor. He had no experience in designing before attending college.
*Lina	Female	Senior	Completed several design courses and senior design project. She did CAD classes in high school and worked at a machine shop during summers while at college.
*Gus	Male	Senior	Completed several design courses and his senior design project. He had no experience in designing before he attended college.
*Len	Male	Junior	Completed two design based courses. He also did CAD in high school.
*Hank	Male	Junior	Completed two design based courses. He had no experience in designing before attending college.
*Vel	Female	Junior	Completed three design based courses. She had no experience in designing prior to attending college.
Professional Engineers			
*Ven	Male	PhD in mechanical engineering	He has been a mechanical engineer for forty years. Specialize in strength of materials.
*Mac	Male	Bachelors in Mechanical engineering	He has been an engineer for over 24 years. Also works as a computer engineer. Owns a machine shop and design and build mechanical equipment as a hobby.
*Lee	Male	Masters in Mechanical engineering	He recently retired. Has been an engineer for forty two years.
*Ray	Male	Bachelors in Mechanical engineering	He has been an engineer for seven years. He does consultation for boiler and food processing plants.

*Pseudonyms

Research Question One.

How do the mental representations (propositions, metaphors, and analogies) of student and professional engineers differ in their problem and solution spaces in terms of their frequency, types, and attributes? Percentage frequency histograms were constructed to illustrate the percentage of propositions, metaphors, and analogies used in the problem space, overlapping space (pro/sol), and solution space of the engineering students and the professional engineers while they solved the design task (see Figures 8 & 9). In addition, pie charts were also constructed to illustrate the percentage of heuristics and formula, within-domain and between-domain analogies used by both groups (see Figures 10 & 11).

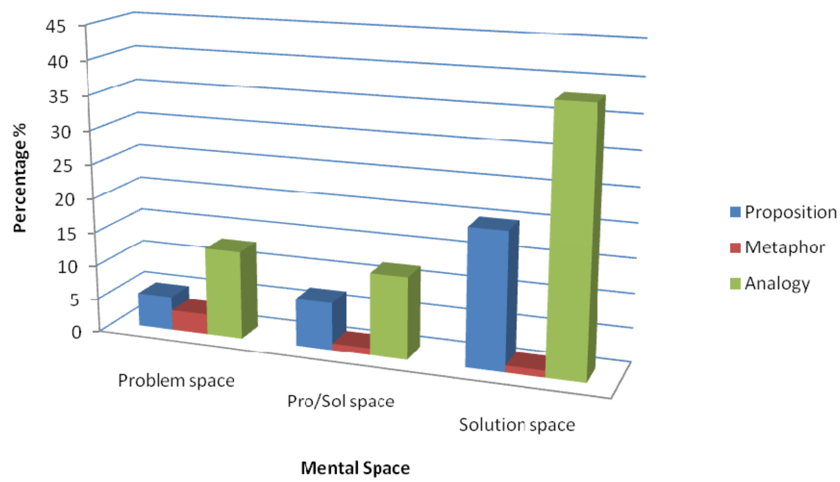


Figure 8. Percentage frequency of proposition, analogy, and metaphor used in the problem, overlapping (pro/sol), and solution spaces of engineering students.

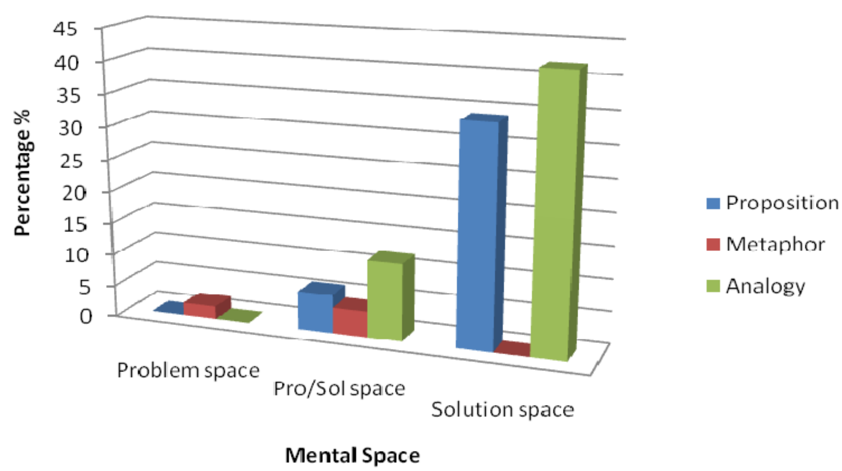


Figure 9. Percentage frequency of proposition, analogy, and metaphor used in the problem, overlapping (pro/sol), and solution spaces of the professional engineers.

Frequency and types of mental representations. Figure 8 illustrates that the engineering students used almost equal percentages of mental representation in their problem and overlapping spaces, 21% and 20% respectively. However, 59% of their mental representations were generated in their solution space. The professional engineers used a very small, 2 %, of their mental representations in their problem space, 22% in their overlapping space, and 76% in their solution space.

The higher percentage use of mental representations within the solution space is not surprising since it is within this space that ideas are primarily conceptualized, developed, and evaluated. Mental representations such as analogies and propositions would logically play an integral role in formulating design ideas, in identifying the strength and weaknesses of these ideas, and in making decisions that are consistent with these representations.

The number of propositions used by the engineering students increased from their problem space to their solution space. Five percent was used in their problem space, 7% in their overlapping space, and 32 % in their solution space. The professional engineers did not use any proposition in their problem space, 6% in their overlapping space, and 34% in their solution space. It was anticipated that the use of proposition would be less in their problem space and more in their overlapping and solution spaces. This proved to be true for both the professional engineers and the engineering students.

The total number of metaphors used was small in comparison to the other mental representations. The engineering students used a total of 4 metaphors (5%) while the professional engineers used a total of 3 metaphors (6%). Two of the metaphors used by the students were in their problem space, 1 was used in their overlapping space and 1 in their solution space. In contrast, 2 of the metaphors used by the professional engineers were in their overlapping space, 1 in their problem space and none in their solution space. Since metaphors primarily help designers to frame and define the design problem (Hey, Linsey, Agogino, & Wood, 2008), it was expected that they would be used more frequently in the problem space and less in the overlapping and solution spaces. Because of the small amount of metaphors used, this was inconclusive. In addition, the types of metaphor used were not from very distant domains and seemed to be influenced by key terms in the design question such as "taxi," and mental images that the designers generated of the conditions in which the taxi is expected to operate. The following are three examples of metaphors used:

> MAC: *…I'm struck by the difficulty of balancing large loads and a passenger on a motorcycle in this rough terrain. My initial thought was some sort of an articulated vehicle that would be attached to the rear of the motorcycle that would carry the passenger and/or luggage and provide the stability.* [Professional engineer]

> LEN: *Let's see, so I'm thinking, try to keep the design small like almost like a compact type car.* [Engineering student]

> GUS: *So I think I would try to modify it to basically act more like a four wheeler or look like a four wheeler…The first imagery was the topography, the location that they were in. I was just like thinking about the tropical island how muddy the roads are how difficult it is to navigate them or not navigate them…* [Engineering student]

The percentage frequency of analogies used by the engineering students was 13% in the problem space, 12% in the overlapping space, and 38% in the solution space. As was the case with the use of propositions, the professional engineers did not use any analogy in their problem space. They used 12% analogy in their overlapping space and 42% in their solution space. It was also expected that analogies would be used less in their problem space and more in their overlapping and solution spaces. This proved to be true for the professional engineers and the engineering students.

Overall, the engineering students surpassed the professional engineers in the percentage of analogies used (63% and 54% respectively). This however differs from findings by Ball, Omerald, and Morley (2004), which indicated that experts displayed greater evidence of analogical reasoning than do novices, irrespective of whether such analogizing is schema-driven or case-driven. It should be noted that while the forgoing findings conflict with research that highlights the superior and more abundant use of analogical reasoning by experts, the percentage use of analogies by the professional engineers in their solution space exceeded those of the engineering students (42% professional engineers, 38% engineering students). This was more consistent with the literature on experts' analogical reasoning (Gentner & Markman, 1997; Hey et al., 2008). Possible reasons for this undulation will be developed in Chapter 5.

Attributes of proposition and analogy. The think-aloud protocol of each participant was examined to determine the proportion of propositions used that were formulas and the proportion used that were heuristics.

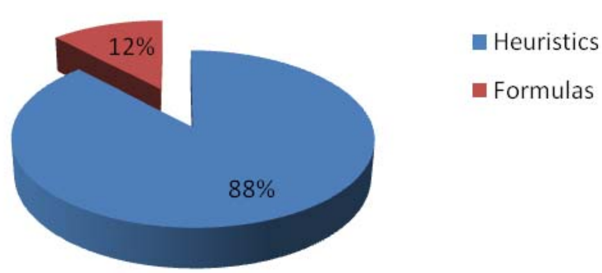


Figure 10. Percentage of propositions used by engineering students

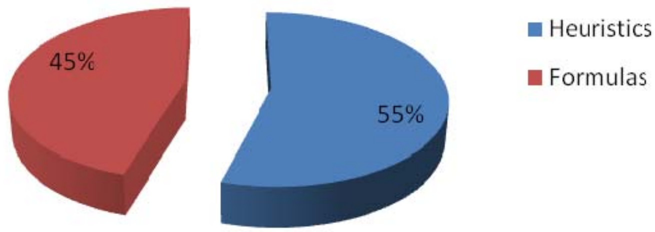


Figure 11. Percentage of propositions used by professional engineers

Figures 10 and 11 respectively depict that the engineering students primarily used heuristics in their engineering design, while the professional engineers used heuristics and formulas more equally. Formulas and heuristics were primarily used to resolve functional issues that the designers encountered in their solution. The following are verbatim reports of two occasions when the engineering students used formulas and two occasions when they used heuristics in their protocol.

> *VEL: "So if that's F and G this would be cosine 30 and then sine 30 or wait the other way around…Then this force would or we could use like F equals MA. Then that force minus the force in the other direction would be equal to MA. Then we could determine which acceleration we would want to calculate the force."* [Engineering student using formula]

> *VEL: "But I know that if we were to draw like forced diagram for that, then it would be something like this… I am not sure exactly how you would find the horsepower, but I know that then you would estimate the force of or the total force of the motorcycle, plus the person on it and probably add a little more weight for packages, or whatever was behind them, or they were carrying"* [Engineering student using formula]

> *DON: "Along with this improved rack comes more weight, so therefore we could have some problem with the horsepower not being sufficient enough."* [Engineering student using heuristic]

> *LEN: "The only problem with that is it might throw off the balance of the bike but you probably just have to put more of a counter weight in the front."* [Engineering student using heuristic]

The following are verbatim reports of two occasions when the professional engineers used formula and two occasions when they used heuristics in their protocol.

> RAY: *"If you're carrying two people and cargo, that's extra weight. You know force, mass times acceleration, and work is force times distance and then horsepower is what …W work over time. So I would look at probably, I don't think you need to go twice as big."* [Professional engineer using formula]

> LEE: *"So in this case it would be like the power has to be more, one over square root…I am sorry, one half of existing maximum power. So you need more than half of that. If this is 20 horsepower then you need 30 horsepower."* [Professional engineer using formula]

> VEN: *"One of the things that concern me is about adding more and more weight to the back of this and going up a steep incline is tipping the thing over backwards with passenger on it."* [Professional engineer using heuristic]

> MAC: *"And so my thinking there maybe I would go to two tires in the rear to provide additional heat dissipation capability, because of the smaller diameter."* [Professional engineer using heuristic]

Similarly, the proportion of analogies used that were within-domain and the proportion that were between-domain were also determined. Figures 12 and 13 illustrate respectively that the engineering students used more within-domain analogies, while the professional engineers used both within-domain and between-domain analogies almost equally. A small percentage of analogies from both groups were identified as unclear because their attribute could not be identified as within-domain or as between-domain.

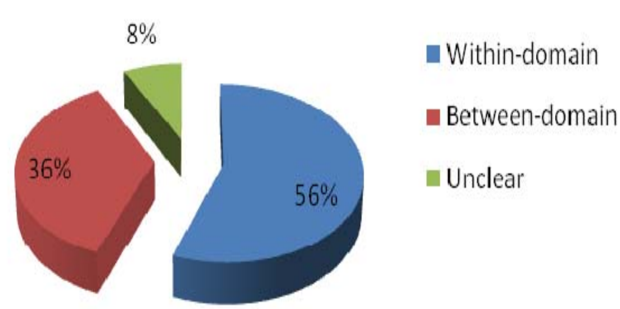


Figure 12. Percentage analogies used by engineering students.

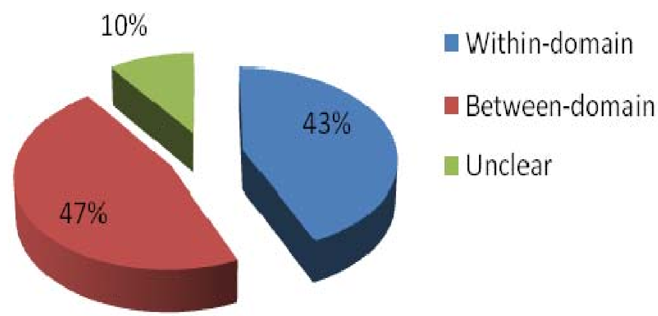


Figure 13. Percentage analogies used by professional engineers.

The following are verbatim reports of two occasions when the engineering students used between-domain analogies and two occasions when they used within-domain analogies.

> GUS: *"That doesn't look like it's too comfortable for the passenger so like thinking back to types of four wheelers I've ridden they always had…here is the seat so I would modify it for the motor cycle."* [Engineering student using between-domain analogy]
>
> LEN: *"The first person would be up here and the second person would be embedded. It's going to be a curved in seating area here…like a scoop…it's going to be more like a scope fit."* [Engineering student using between-domain analogy]
>
> LINA: *"Let's see, a device to prevent the… theft of helmets. I know a lot of motorcycles have something where in order to lift up the seat you actually have to put in your key and underneath the seat you have these little metallic…like little brackets basically."* [Engineering student using within-domain analogy]
>
> DON: *"I'm trying to think of bike-locks for example you know there's chain locks, there's cable locks."* [Engineering student using within-domain analogy]

The following are examples of two between-domains analogies and two within-domain analogies used by the professional engineers.

> RAY: *"I wonder if this lock isn't automatic for the release of the helmet. Well you know cars have, you don't actually put your key in the car anymore to open up the door."* [Professional engineer using between-domain analogy]

MAC: *"This thought is driven by my ergonomic chair that I have in my office that's actually quite comfortable and has the split..."* [Professional engineer using between-domain analogy]

RAY: *"I am contemplating if we need to you know the Harleys I see out there. It seems like the wheel might be further apart."* [Professional engineer using within-domain analogy]

VEN: *"I'm trying to picture in my mind since we are talking about motorcycles and since I don't know a lot about them, I am trying to picture essentially other kinds of motorcycles and why they may be inherently stable."* [Professional engineer using within-domain analogy]

Two examples of analogies that were used but whose sources were unclear are:

VEL: *I guess something like that but then it would be like a box shape.* [Engineering student]

DON: *I think in this area here if some sort of, I don't know, maybe a heat resistant cloth or some sort of material that you could have made that would fit over the front here.* [Engineering student]

The use of both within-domain and between-domain analogies by the engineering students and professional engineers is consistent with Christensen and Schunn's (2007) study that showed that, unlike science, between-domain analogies are quite frequent in engineering design, almost as frequent as within-domain analogies, suggesting they have important functions in design cognition.

Research Question Two

How does the metacognitive regulation (planning, monitoring, and evaluation) of student and professional engineers differ in their problem and solution spaces in terms of their frequency and characteristics? Percentage frequency histograms were constructed to compare the planning, monitoring, and evaluation of the engineering students and professional engineers in the problem space, overlapping space (prob/sol), and solution space. As illustrated in Figures 14 and 15 both groups' planning activities decreased as they progressed mentally from their problem space to their solution space. Also, both groups' monitoring and evaluation activities increased as they progressed mentally from their problem space to their solution space. Overall, the engineering students showed a higher percentage of planning activities (28%) when compared to the professional engineers (16%). The professional engineers overall displayed almost two times the percentage of evaluation activity (33%), in comparison to the engineering students (17%). In addition, the professional engineers displayed a greater proportion of monitoring and evaluation activities in their solution space when compared with the engineering students. The professional engineers used 40% of their monitoring activities and 31% of their evaluation activities in their solution space, while the engineering students used 33% of their monitoring activities and 12% of their evaluation activities in their solution space.

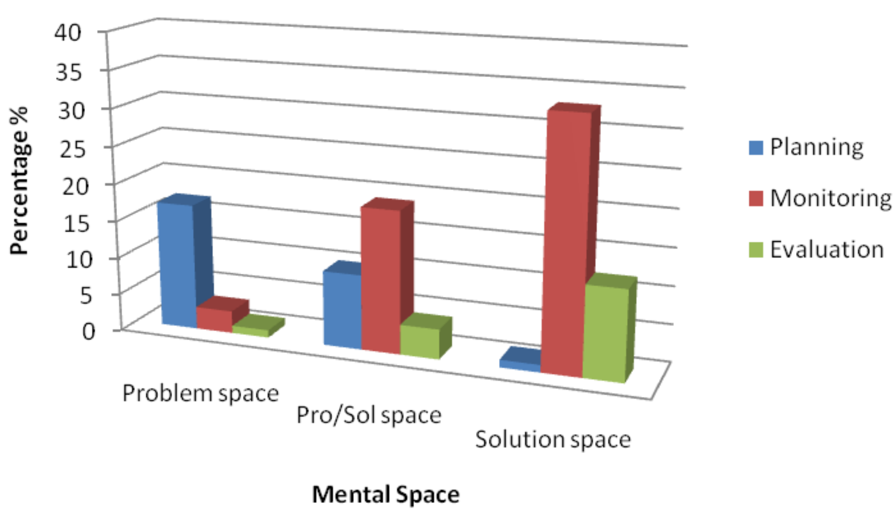


Figure 14. Percentage frequency of planning, monitoring, and evaluation used in the problem, overlapping (pro/sol), and solution spaces of the engineering students.

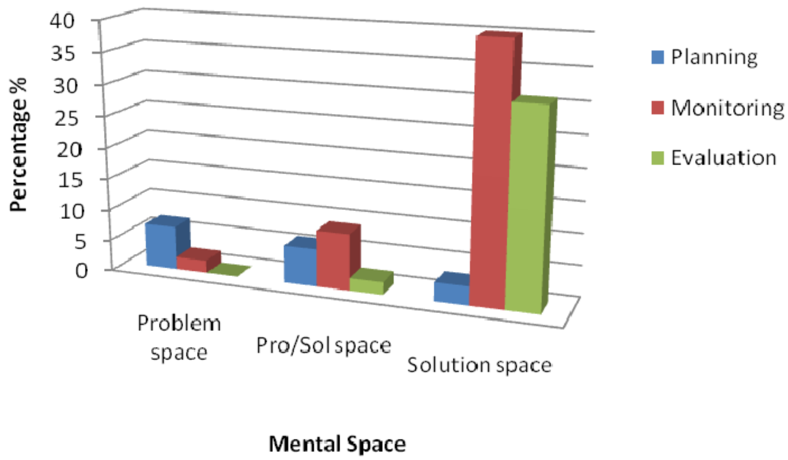


Figure 15. Percentage frequency of planning, monitoring, and evaluation used in the problem, overlapping (pro/sol), and solution spaces of the professional engineers.

It was assumed that planning would be more dominant in the problem space and less dominant in the overlapping and solution spaces. This assumption proved to be true for both the engineering students and professional engineers. The higher percentage of time spent planning by the engineering students does not resonate with findings from other studies, which showed that individuals with less expertise in solving a particular type of problem spend less time in global "up front" planning and qualitatively analyzing the problem, than do experts across age levels and from different areas of expertise (Bransford, Brown, & Cocking, 2000; Chi, Glaser, & Farr, 1988). The variance of this finding with the literature on novices and experts could be explained by the presence of several variables such as how the engineering students' were taught design and the type of design they are engaged in solving. This is explicated further in the chapter 5.

The other assumption was that monitoring activities will be less dominant in their problem space and more dominant in their overlapping and solution spaces. This assumption proved to be true for both the engineering students and professional engineers. The final assumption was that evaluation activities will be less dominant in the problem space and more dominant in the overlapping space and the solution space. Like the previous assumption, this was true for both the engineering students and professional engineers.

Metacognitive regulation characteristics. Table 4 compares the main characteristics of the engineering students and professional engineers planning, monitoring, and evaluation activities.

Table 3

Characteristics of Metacognitive Regulation

Metacognitive Regulation	**Characteristics**	
	Engineering Students	**Professional Engineers**
Planning	Spend more time planning than the professional engineers. Sub-problems are prioritized to determine which to tackle first. "*So looking over these trying to prioritize which ones are most important and which one to start first.*" Planning sometimes was influenced by mental imagery of the conditions in which the component has to function. *"Well the first imagery was the topography, the location that they were in."* Mental imagery of the operational condition seems to precede the generation of metaphor. "*So I think I would try to modify it to basically act more like a four wheeler or look like a four wheeler…The first imagery was the topography, the location that they were in. I was just like thinking about the tropical island how muddy the roads are how difficult it is to navigate them or not navigate them."* Uses metaphor to help in the framing and understanding the problem. "*So I think I would modify it basically to act more like a four wheeler."*	Spend less time planning than engineering students. Their planning strategies were more influenced by the cost constraint and comfort of the riders. *"So they talk about the price has to be fixed and that's very important not to exceed okay." "Not going to have the staff bend over all the time, so handle bars for taxi drivers ergonomics."* Like the engineering students, planning sometimes was influenced by mental imagery of the conditions in which the component has to function. *"The first thing I am going to look at is sizing it for the rain and rugged terrain."* Mental imagery of the operational condition seems to precede the generation of metaphor. *"I'm struck by the difficulty of balancing large loads and a passenger on a motorcycle in this rough terrain. My initial thought was some sort of an articulated vehicle that would be attached to the rear of the motorcycle that would carry the passenger and/or luggage and provide the stability."*

(continued)

Table 3 (continued)

Metacognitive Regulation	Characteristics	
	Engineering Students	**Professional Engineers**
Planning	When a metaphor/analogy is used it causes the planning to be reflective of features implicit to the metaphorical or analogical features. *“So what I am doing right now is trying to think of other road vehicles, their seating like for example four wheelers, their seating and the racks are much wider, so we could possibly make the rear a little wider by extending the frame forward…”* Ask questions about constraints that are not stipulated in the design brief. *“How wide are the paths really?” “How long the rainy season usually last?”*	Their area of expertise influence how they identified weakness and how they strategize their approach. *“So being one of my point of expertise is the strength of things…I would do something to connect this point.”* Planning strategies are more driven by engineering science principles rather than analogical features. *“So I lowered the centre of gravity of the load and extended the wheel-base for stability. Okay I have a initial concept for moving forward.”*
Monitoring	The use of analogy seems to induce metacognitive activity such as self-testing of the superior quality of one design conceptualization over another. *“…I am trying to think of bike looks…you know there’s chains locks, there’s cable lock…actually stainless steel would probably be better for the helmet…aluminum is strong but definitely not as strong as steel and in this case I think it is important for the strength than the weight.”* When the solution of a functional issue is difficult they may use between-domain analogy to find a solution. “*We had a presentation messing around with fuel air ratio for an eco challenge. So I just know that if you put too much fuel in you’re not going to light anything. So that’s why I’d mess around with the air ratio carburetor.”* Safety seems to be the main factor that drives the assessment and optimization of the quality of a solution. *“The exhaust I think might cause a problem with the rider. I think the more shielding would have to be implemented to prevent the rider or any cargo from burning.”* Within-domain analogies were used more frequently than between-domain analogies and heuristics were used more frequently than formulas.	Depended more on engineering science principles and heuristics. *“You are carrying two people and cargo, that’s extra weight. You know force mass times acceleration and work is force times distance and then power, horse power is what W work over time. So I would look at probably, I don’t think you need to go twice as big”* Most of the monitoring activities focus at improving the customer safety and comfort. “*But this I mean to make the passenger more comfortable we’ve got to do a better job of seating*” Closely related to safety they also focus on structural integrity of the design conceptualization more than the engineering students. *“That can be in fact a comfortable seat…I am thinking right now about the structural rigidity about the vehicle. I like the fixed tunnel that runs from the rear of the vehicle, where the load deck is up to the frame recognizing that if those are stressed panels they’ll provide good torsional rigidity.”* Uses almost equal amount of within-domain and between-domain analogies, heuristics and formulas.

(continued)

Table 3 (continued)

Metacognitive Regulation	Characteristics	
	Engineering Students	**Professional Engineers**
Evaluation	Spent less time on evaluation	Spent more time on evaluation
	Adherence to engineering science principles and cost ultimately determines the judgment of the superiority of one design conceptualization over another. *"Right now I have two solutions that I could go with…the side car which takes care of the passenger and the cargo. I think I will just put that down there. Also might help out with stability, although it will cost in terms of needing more horse power for the motor."*	Personal experience and exemplars are used to evaluate the quality of a conceptualization. Often when they come up against roadblock in their solution they use within-domain analogies. *"The Hog, the Gold Wings…they are essentially much more comfortable kind of touring things…that is why I'm trying to picture them in my mind."*
	For some of the students safety and comfort were criteria used to evaluate. "*There I guess it make the rear seating more comfortable. It's more like a back and side rest, so a person is actually in place rather than feeling like they might fall off. It would also have to be equipped with foot pegs for the passenger."*	Like the engineering students, cost, safety, comfort, and adherence to engineering science principles were criteria for making judgment about the superiority of one conceptualization over the other. *"If you go with two tires you're essentially creating a tricycle and a tricycle will tip from one wheel to the other and provide unusual and undesirable dynamics. A conventional motorcycle with an articulated pivot, point to a small rickshaw in the back. The rickshaw would provide stable ride for the passenger to get in and out, carry lots of load…"*

Research Question Three

How do the mental representations and metacognitive regulation of students and professional engineers relate to their overall engineering design strategy? The segment distribution charts in Figures 16 and 17 illustrate how the mental representations of the engineering students and professional engineers are distributed over time and in relationship to their planning, monitoring, and evaluation. The charts show that both the engineering students and the professional engineers use different degrees of propositions, metaphors, and (or) analogies, in their planning. Only three of the engineering students (Don, Gus, & Len) and one professional engineer (Mac) used metaphors while they were planning. One engineering student (Len) and a professional engineer (Mac) used a metaphor while carrying out monitoring activities. Additionally, during the monitoring activities of the student and professional engineers, analogies and propositions were used; except for one engineering student, (Gus) who used only analogies.

All the engineering students used only analogies in their evaluation, except for one (Hank) who used both analogies and propositions. In contrast, two of the four professional engineers used both analogies and propositions in their evaluation, one used only analogies, and one did not use any mental representation. Most of the mental representations were used by the engineering students and professional engineers while they were monitoring their design solution. One engineering student (Hank) deviated from this pattern. He used most of his mental representation during evaluation.

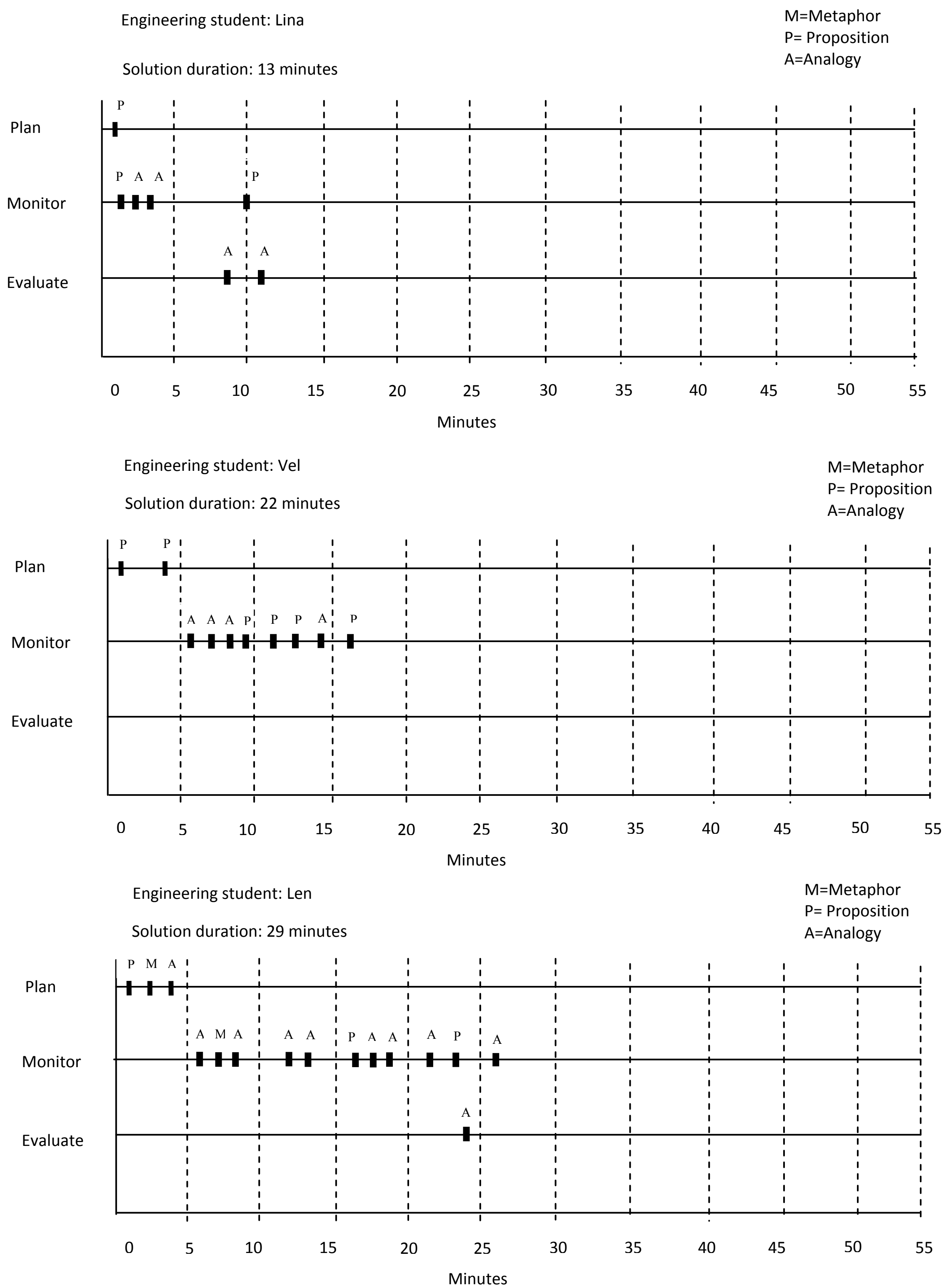


Figure 16. Segment distribution charts for engineering students (continued).

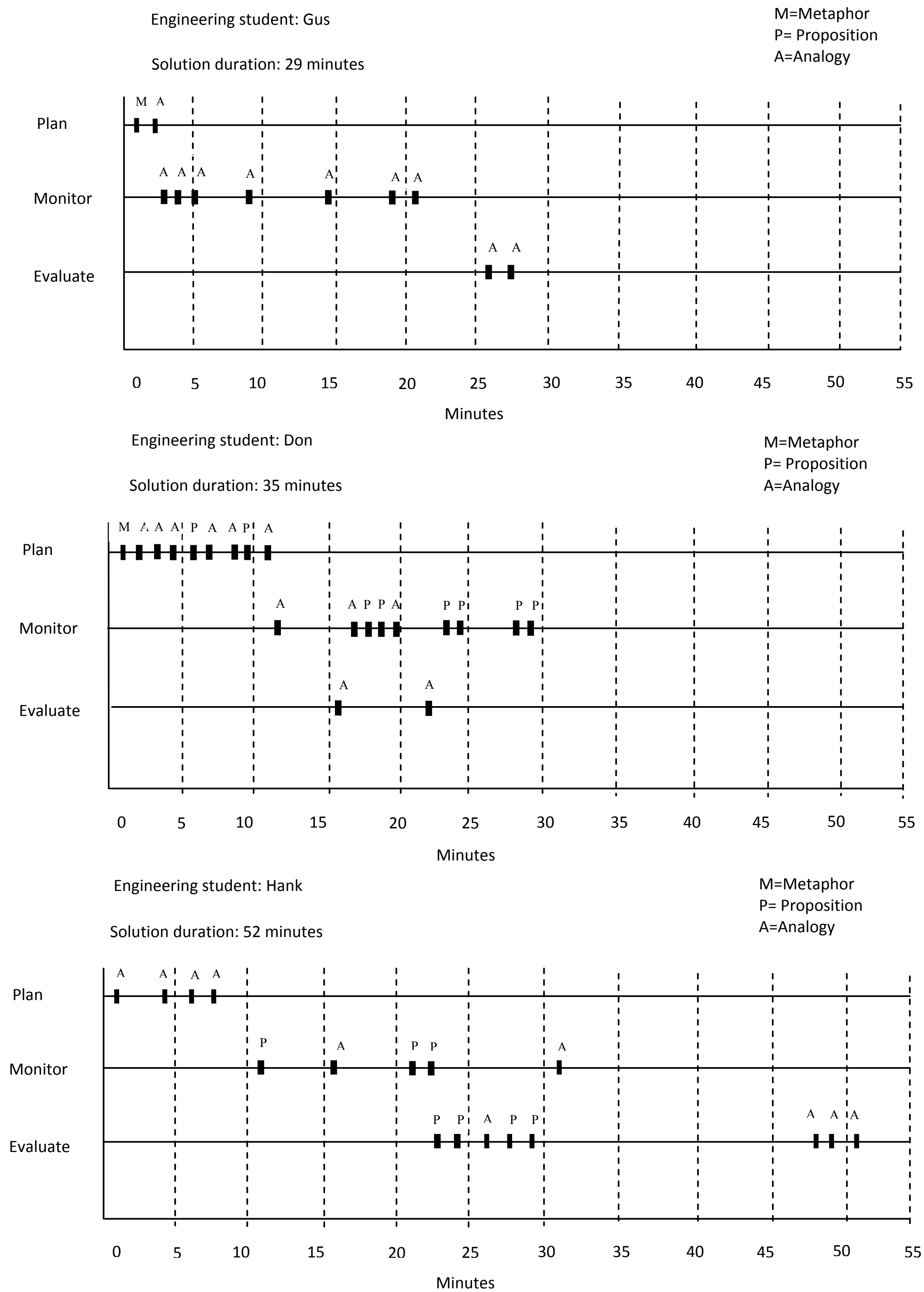


Figure 16. Segment distribution charts for engineering students.

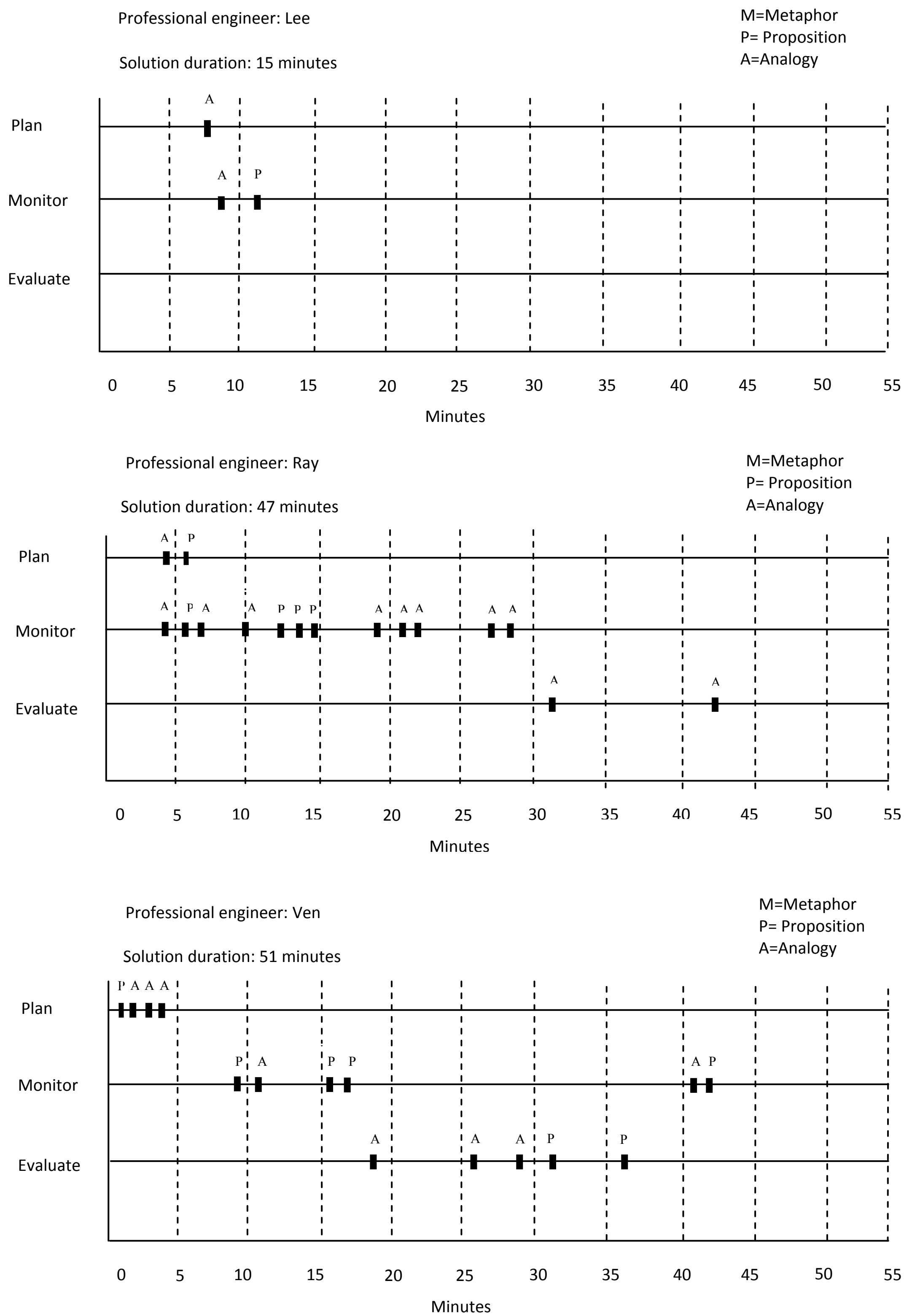


Figure 17. Segment distribution charts for professional engineers (continued).

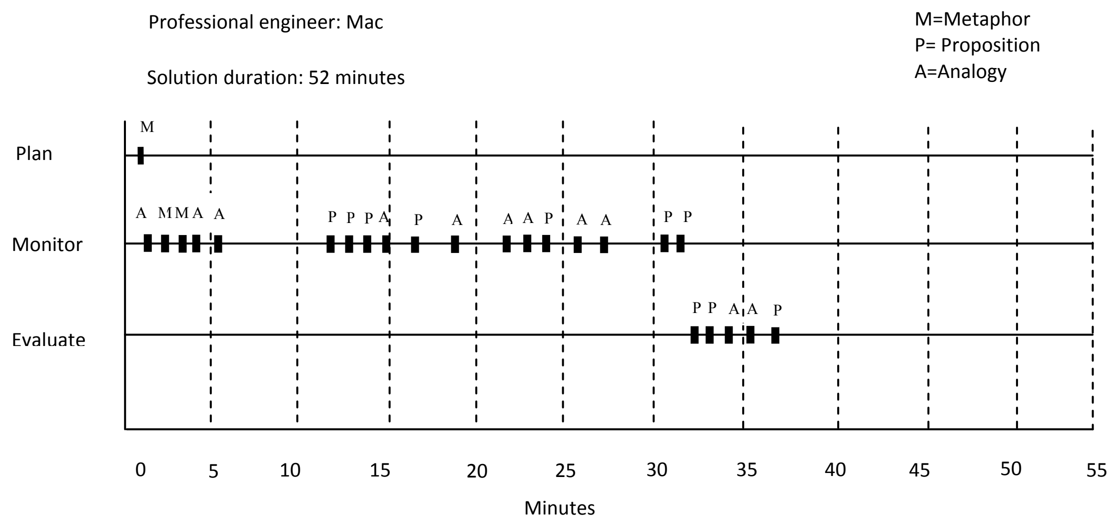


Figure 17. Segment distribution charts for professional engineers.

The network diagram in Figures 18 to 21 illustrate that there is some difference in the pattern of exchange between the problem and solution spaces of the engineering student and professional engineer that took the shortest time. The exchange between their problem and solution spaces is illustrated in the diagrams by the space in the middle referred to as the *overlapping space*. The numbers in bracket represent the time in minutes as the participant progressed in solving the design task. The diagrams show that the engineering student spent less time than the professional engineer gathering and rechecking data regarding constraints, criteria, and other information that they considered relevant from the problem space. The patterns for the engineering student and professional engineer who took the longest time were more similar.

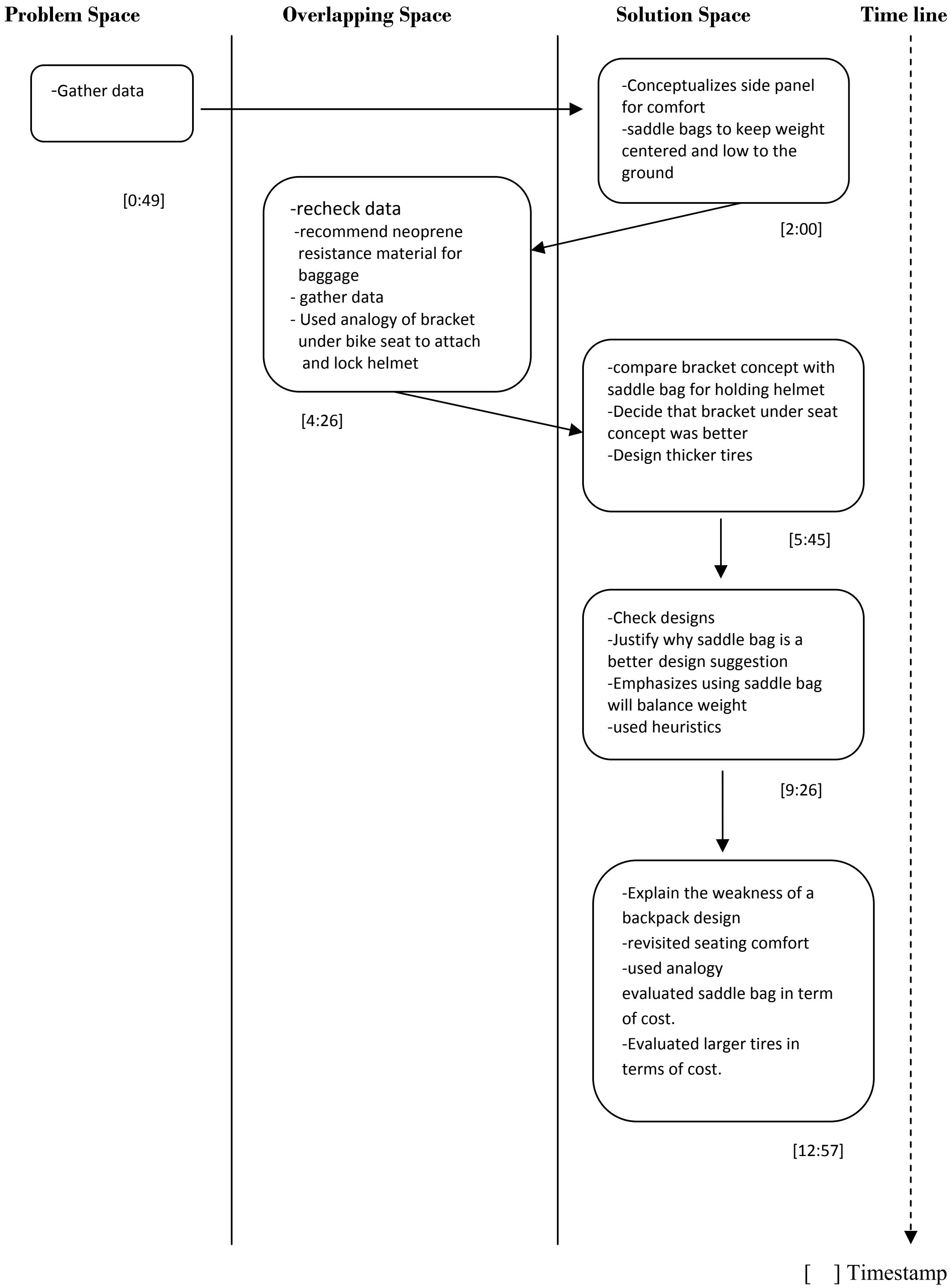


Figure 18. Network diagram depicting the cognitive strategy of the engineering student with the shortest design time.

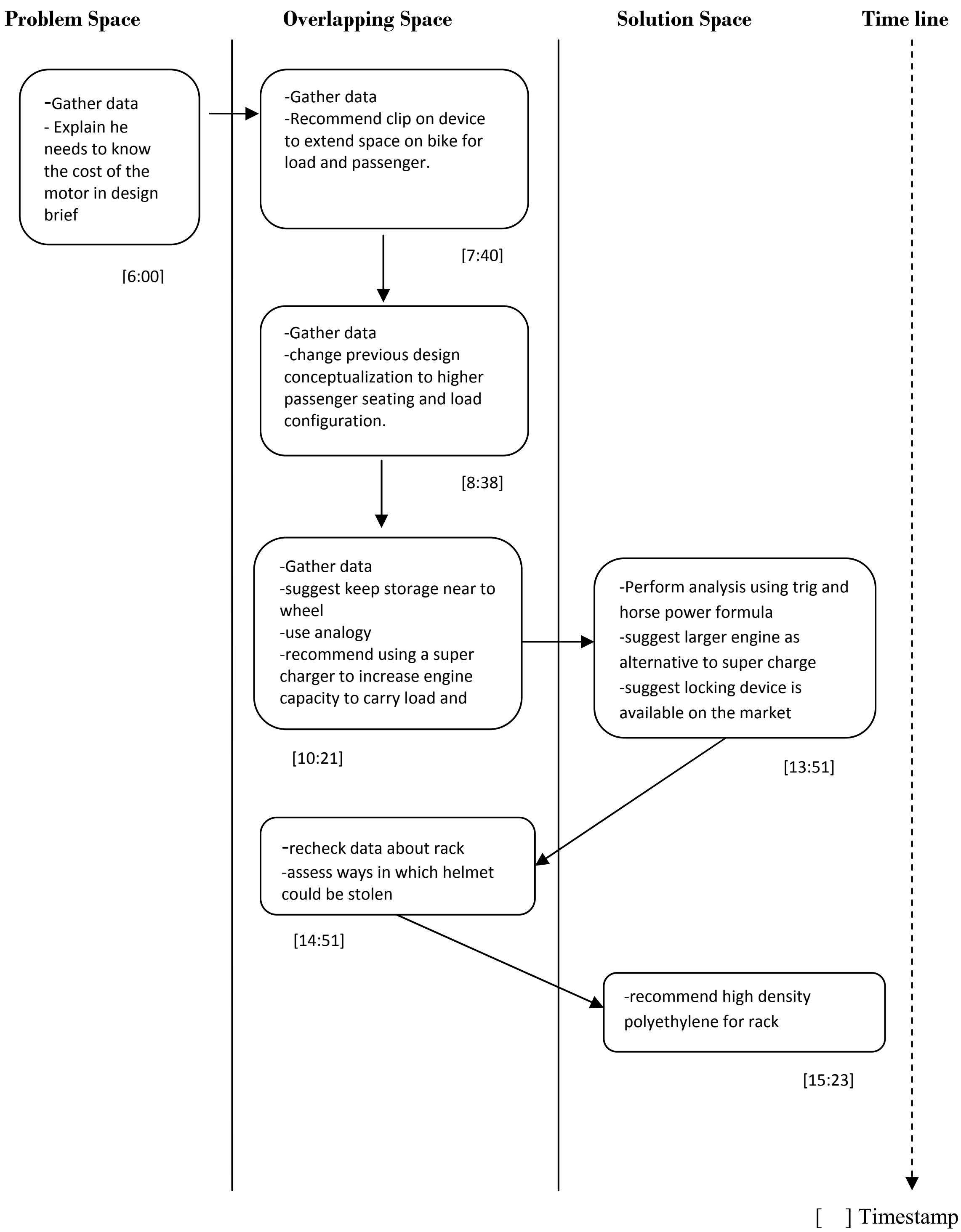


Figure 19. Network diagram depicting the cognitive strategy of the professional engineer with the shortest design time.

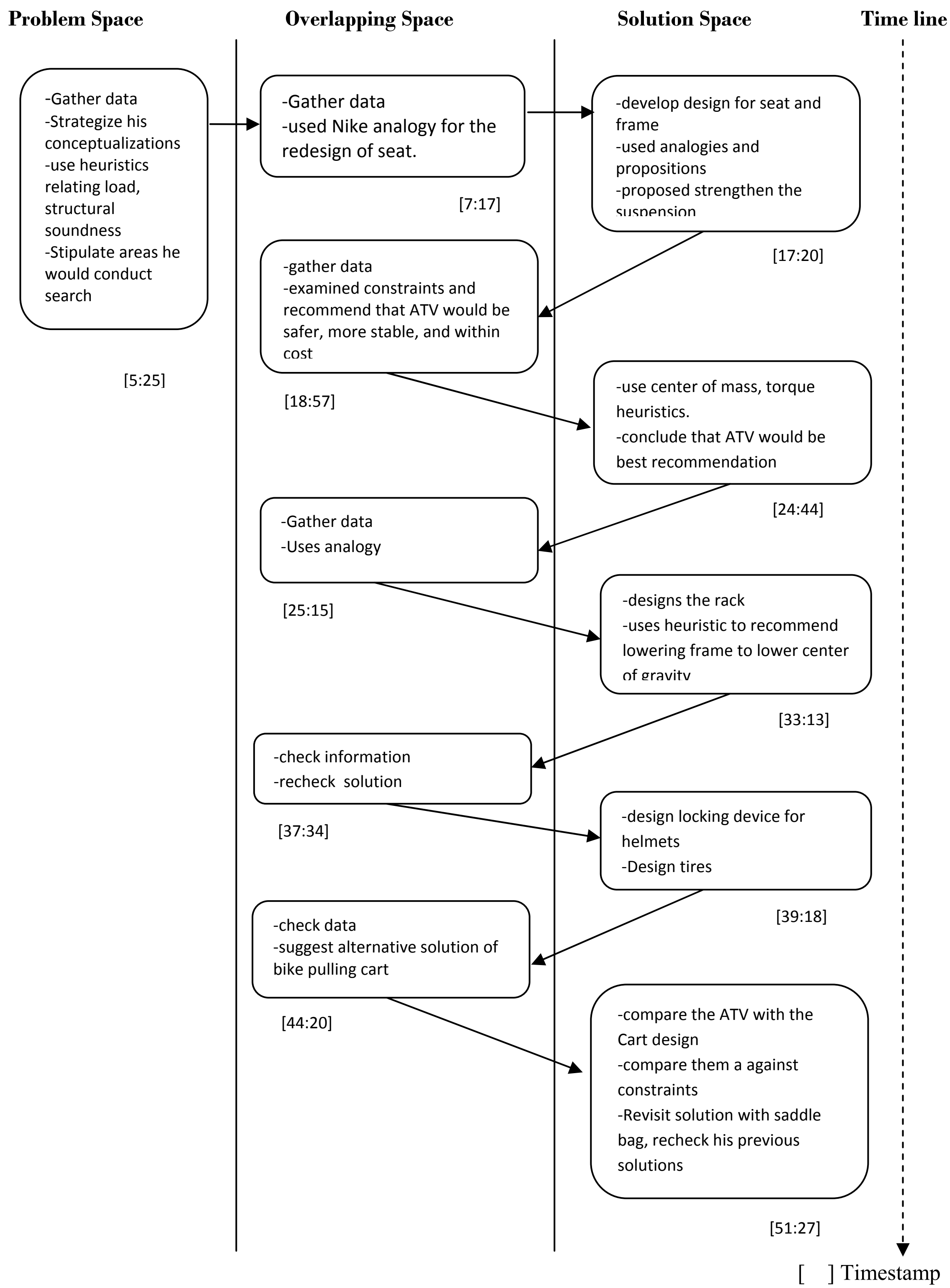


Figure 20. Network diagram depicting the cognitive strategy of the engineering student with the longest design time.

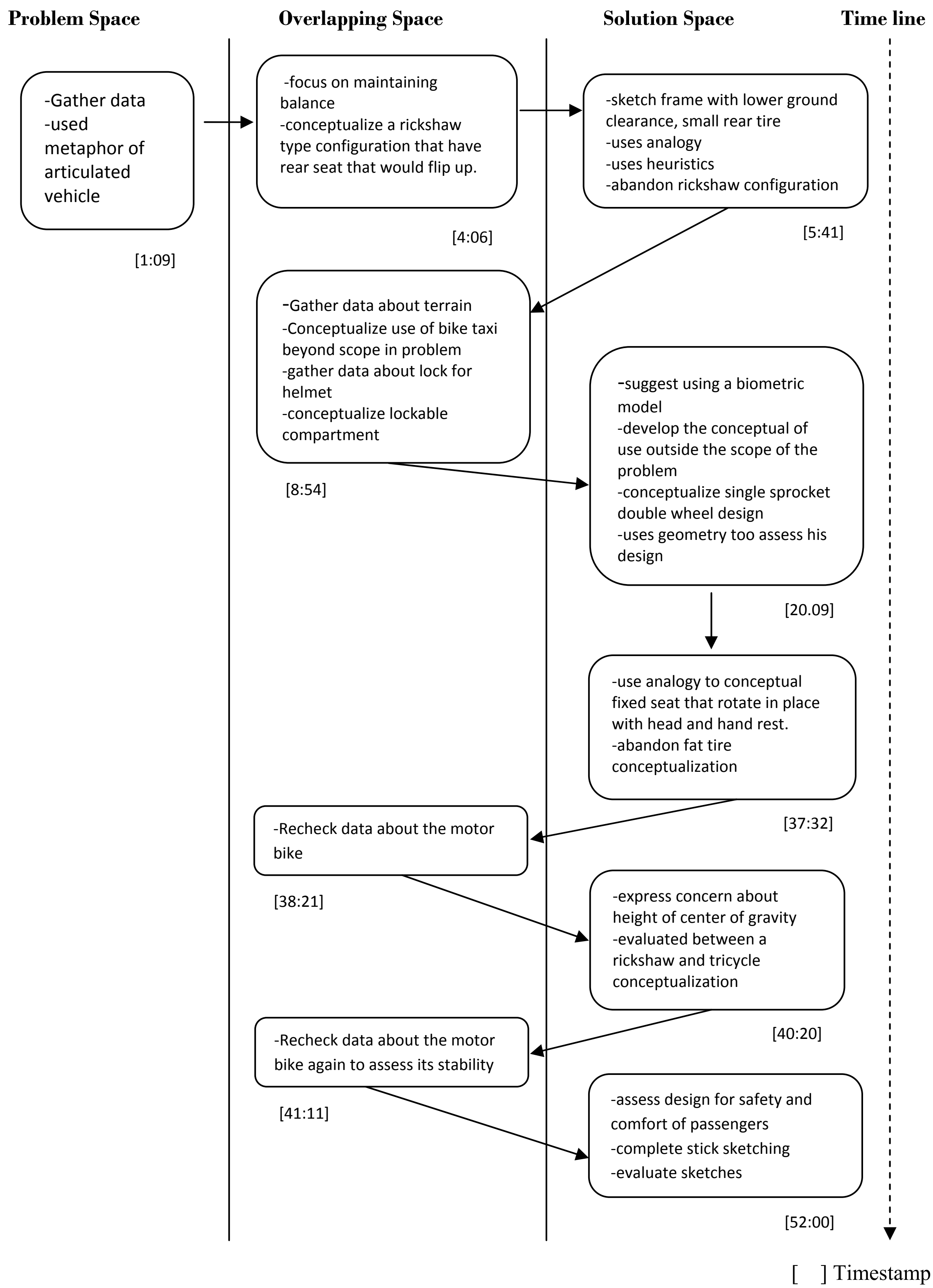


Figure 21. Network diagram depicting the cognitive strategy of the professional engineer with the longest design time.

A better idea of the association between the cognitive pattern and metacognitive regulation of the student and professional engineers with the shortest times and the student and professional engineers with the longest times can be seen by supplementing the previous network diagrams with individual matrix tables. The matrix in Table 4 illustrates that the engineering student with the shortest time for solving the design task utilized most of her mental representation and regulatory activities in her solution space. Her total number of metal representation (proposition and analogy) and metacognitive regulation (monitoring and evaluation) in the solution space were equal.

Table 4

Matrix of the Engineering Student who Spent the Shortest Time to Solve the Design Task

	Mental Space			
Mental Representation and Metacognition	Problem space	Overlapping Space	Solution space	Total
Proposition		1	3	4
Metaphor				
Analogy		2	2	4
Total		3	5	8
Planning	1			1
Monitoring		1	2	3
Evaluation			3	3
Total	1	1	5	7

As illustrated in Table 5, the professional engineer who spent the shortest time to solve the design task, utilized most of his mental representations in the overlapping space and equal amount of metacognitive regulatory activities in his problem and solution spaces. Interestingly, unlike the other engineers he did not show any sign of performing evaluation in any of his mental spaces.

Table 5

Matrix of the Professional Engineer who Spent the Shortest time to Solve the Design Task

	Mental Space			
Mental Representation and Metacognition	Problem space	Overlapping space	Solution space	Total
Proposition			1	1
Metaphor				
Analogy		2		2
Total		2	1	3
Planning	4	1		5
Monitoring			4	4
Evaluation				
Total	4	1	4	9

Table 6

Matrix of the Engineering Student who Spent the Longest Time to Solve the Design Task

	Mental Space			
Mental Representation and Metacognition	Problem space	Overlapping space	Solution space	Total
Proposition	1		6	7
Metaphor				
Analogy	2	4	5	11
Total	3	4	11	18
Planning	5	1		6
Monitoring	4	4	9	17
Evaluation		2	4	7
Total	9	7	13	30

Table 6 illustrates that the student who spent the longest time to solve the design task used most of his mental representation in his solution space. His metacognitive regulation was lowest in the overlapping space, higher in the problem space, and highest in the solution space. In fact he used an almost equal amount of analogy and proposition in his solution space and his monitoring activity was just over twice his evaluation activity. In contrast, the professional engineer who spent the longest time to solve the design task, used most of his mental representation and metacognitive regulation in his solution space. His use of proposition and analogy was almost equal and his monitoring and evaluation activities were equal (see Table 7).

Table 7

Matrix of the Professional Engineer who Spent the Longest Time to Solve the Design Task

	Mental Space			
Mental Representation and Metacognition	Problem space	Overlapping space	Solution space	Total
Proposition		1	10	11
Metaphor	1	2		3
Analogy			9	9
Total	1	3	19	23
Planning	2	3	2	7
Monitoring		6	14	20
Evaluation			14	14
Total	2	9	30	41

Engineering design strategy. There were several differences and similarities in the engineering design strategy used by the engineering students and professional engineers. All the participants followed the iterative engineering design process; however, the professional engineers on an average took a longer time to solve the design task than the engineering students (Professional engineers 47.17 minutes; Engineering students 30.17 minutes). Again this resonates with the findings of Atman et al. (2007), which showed that experts spend significantly more time overall than the novice to solve the same design task. It should be noted however that the experts in Atman's study were expert engineering designers, not expert playground designers, and this may have accounted for the expert spending more time on the design task. Similarly, both the engineering students and professional engineers did not have any experience designing motor bikes.

Another obvious similarity between both groups was the iterative process that was reflected by going back and forth between the problem space and solution space. They both checked with the design brief or ask questions to verify or increase their understanding of the problem. This sometimes led to the emergence of a different or modified conceptualization, which closely reflects findings from the literature (Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996). The following is the verbatim protocol of one designer who navigated between the problem and solution spaces, gathering data that subsequently led to the emergence of a modified conceptualization.

> MAC*: I see that there's a large amount of rainfall, the instructions do not talk about the type of terrain whether I need to navigate mud or if this is more rocky terrain. Make an assumption that it's relatively rocky terrain. If in fact that assumption is correct this configuration may not be appropriate as you would need the increased ground clearance to get through muddy ruts. And the design problem that they want is to both increase the cargo capacity and make the rear seating more comfortable. My concern is that I do in fact need to provide the same amount of luggage along with the passenger as opposed to having two vehicles to solve the problem. And I want to go back again to the requirement and see what the intended users are these will be leased as taxis let's see.*

Similar to the findings of Atman et al. (2007), both experts and novices asked questions, to clarify information that was given in the design brief. Overall the professional engineers asked more questions than the student. Examples of two questions are:

VEN*: This terrain that you are talking about is quite hilly. Are the road conditions pretty bad as well?* [Professional engineer]

LEN: "How long does the rainy season usually last?" [Engineering student]

In addition, in their scoping, the professional engineers sometimes consider a broader aspect or scope of the design problem.

MAC*: My intuition is there is a market for this vehicle. You will see the private use of these farmers, merchants, workers and they will use these as small pick-ups. So in other words they will do away with the use of the passenger altogether and they will want a load deck for carrying materials, tools etc.* [Professional engineer]

The quality of each solution was not evaluated since the research objective was to examine cognitive processes rather than the product of the solution. However, the general design recommendation from both groups was a motorbike with a carriage compartment at the back, flatter, lower seats with a back rest, broader wheels and locks to secure the helmets. There was remarkable similarity in the alternative solutions of both the engineering students and the professional engineers. For example, both groups considered using a saddle bag in the center of the bike, a ATV type vehicle with four wheels, ATV type vehicle with three wheels, a bike with a passenger carriage to the side, and a bike with a luggage carriage that is pull at the back.

Finally, Spearman correlation tests were conducted to explore the relationship between mental representation and metacognitive regulation; proposition and monitoring; analogy and monitoring; proposition and evaluation; analogy and evaluation, proposition and planning; and analogy and planning. The spearman correlation values and scatter plot diagram are displayed in Appendix E.

Summary of Findings

A synthesis of all the data generated from the use of both statistical and qualitative tools to answer the three research questions that guided this study, resulted in seven major findings. They are:

- The professional engineers and engineering students increased their use of mental representations as they moved from the problem space to the solution space, using most of their mental representations in the solution space.
- The overall use of analogies by the engineering students exceeded those of the professional engineers; the professional engineers, however, use more analogies within the solution space than do the engineering students.
- The engineering students' used more within-domain analogies than between-domain analogies, while the professional engineers used almost equal amount of between-domain and within-domain analogies.
- The engineering students used significantly more heuristics than formulas while the professional engineers used more formulas than heuristics, but the difference was not substantial.
- The planning activity of both the professional engineers and the engineering students decrease as they moved from the problem space to the solution space, while their monitoring and evaluation activities increase. The professional engineers exhibited more monitoring activities and significantly more evaluation activities in the solution space, while the engineering students did more planning in the problem space.
- The engineering students and the professional engineers used most of their mental representations when they were monitoring their design conceptualization.
- Overall, the metacognitive regulatory activities of the professional engineers and the engineering students were similar. The experts' planning and monitoring tend to be driven by heuristics and formulas based on engineering science, while the engineering students planning and monitoring tend to be influenced by analogical comparisons and heuristics.

Chapter 5

Discussion

The results of this study paint a picture of how four professional engineers differ in their approach to a conceptual engineering design task from six engineering students, by focusing on how they use metal representations (propositions, metaphors, and analogies) throughout their mental spaces (problem space, overlapping space, and solution space) and during metacognitive regulation (planning, monitoring, and evaluation). Five major conclusions are drawn from the findings. They are:

1. The use of mental representation such as propositions, analogies, and metaphors by experts and novice engineering designers in the different mental spaces are important in engineering design.

2. Expert engineering designers use analogies differently in their solution space than do novice engineering designers.

3. Expert engineering designers rely on within-domain analogies, between-domain analogies, heuristics, and formulas differently from novice engineering designers.

4. Analogies and propositions play an important role in the monitoring activities of both experts and novices.

5. In engineering design, evaluation plays a larger role in the solution space of expert designers, while the novice designers tend to do more planning in the problem space.

This chapter will expand on each conclusion. The chapter is organized into two main sections: (a) conclusions and discussion of the findings and (b) recommendations for engineering and technology education curriculum and instruction, engineering practice, and future research.

Conclusions

Conclusion # 1: The use of mental representation such as propositions, analogies, and metaphors by expert and novice engineering designers in the different mental spaces are important in engineering design. This conclusion is relevant in view of the need to better understand the cognitive process of engineering designers. Speaking about the domain of scientific enquiry, Klahr and Dunbar (1988) stipulated that scientific discovery has two primary spaces, the hypothesis space and the experimental space. According to Klahr (2000), these spaces are "sufficiently different that they require different representations, different operators for moving about in the space, and different criteria for what constitutes progress in the space" (p. 14).

Other researchers (Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996) spoke about two types of space in respect to engineering design, the problem space and the solution space. Similar to the spaces in scientific discovery, the types of mental representations in design varies in the problem and solution spaces of designers. In fact, within the solution space, solutions are generated by recalling forms or graphical representations and functions. In addition, ideas are evaluated by comparison with the laws of nature, capability of technology, and the requirements of the design problem itself (Ullman, 2003). Mental representations such as analogies and propositions would logically play an integral role in formulating design ideas, to evaluate them, and to make final decisions that are consistent with the design requirements and their representations. The findings from the protocols indicate that the frequency of use of the various types of mental representations vary in each of these mental spaces, and the use of analogy and propositions will be stronger, particularly within the solution space.

Conclusion # 2: Expert engineering designers use analogies differently in their solution space than do novice engineering designers. This conclusion relates to the second finding. The higher percentage use of analogies by the engineering students was one of the surprising findings of this study. The literature on analogical reasoning shows that analogies are important cognitive tools in design problem solving (Daugherty & Mentzer, 2008; Hey, Lensey, Agogino, & Wood, 2008; Lewis, 2008). A study by Ball, Omerald, and Morley (2004), showed that experts displayed greater evidence of analogical reasoning than do novices, irrespective of whether such analogizing is schema-driven or case-driven. One explanation for this obvious disparity is the type of question and the amount of time the students spend within the problem space and the overlapping space. The retrospective protocols of both groups indicated that the participants did not have any experience in solving that type of design problem before, and except for one student who recently purchased a motorcycle, and one expert who owned a motorcycle for a short time when he was younger, none were fully conversant about motorcycles. Because of the difficulty of the problem, the students spent more time planning in the problem space. They also used more analogies in both the problem space and the overlapping space. Not being acquainted with this type of engineering design problem would naturally cause the students to use more analogical representations to understand and frame the problem, and to create mental models from which they generate solutions. The professional engineers' general experience and confidence, however, would cause them to immediately start exploring the solution space. This may account for the professional engineers using more analogies than the engineering students within the solution space.

Conclusion # 3: Expert engineering designers rely on within-domain analogies, between-domain analogies, heuristics, and formulas differently from novice engineering designers. This conclusion concurs with findings in design studies that both between-domain and within-domain analogies are used by experts and novices in design (Casakin, 2003; Christensen & Schunn, 2007). Casakin also found that novices and experts used more between-domain analogies than within-domain analogies. The findings of this study show that the novices used more within-domain analogies, and the experts used more between-domain analogies. This variance may be explained partly by the research method that was used. Casakin used an experimental setup in which visually analogous displays were provided and the participants were instructed to use analogies. This study differs in that it was non-experimental and no visual prompting or instruction to use analogies was provided; the participants were simply required to solve a design task.

Christensen and Schunn explanation of the use of the various types of analogies may offer some insight in the findings that relate to conclusion number 3. They claimed that problem-identifying analogies were mainly within-domain, explanatory analogies were mainly between-domain, and problem-solving analogies were a mixture of within- and between-domain analogies. The engineering students tend to spend more time in a problem identification mode than a problem-solving mode, possibly because of the challenging nature of the design problem, while the professional engineers were more in a problem-solving mode as was seen by their almost equal use of both types of analogies.

Propositions such as heuristics, math formulas, and engineering science formulas are vital to engineering design problem solving (Cross, 2002; Ullman, 2003). Both experts and novices use them in engineering design. The findings of this study indicate that the engineering students relied more on heuristics than on engineering science formulas. They used more analogical representations and heuristics in their planning and monitoring, while the professional engineers tend to rely more on engineering science formulas and heuristics in their planning and monitoring. This is consistent with research findings which show that outstanding designers rely implicitly or explicitly on first principles in the origination and development of concepts (Cross, 2004).

The fact that this type of design problem represents uncharted territory for most of the engineering students, might explain why they used heuristics or rule of thumb in search for possible solutions. According to Davidson, Deuser, and Sternberg (1995), heuristics can be used to construct mental representations when a problem solver finds that a current representation is not working. Another reason might be the cognitive cost that is involved in using heuristics. Some students found it difficult to remember certain engineering science formula. Using heuristics, rule of thumb, or short-cuts is cognitively economical, and reduces the cognitive load that students have to endure in trying to remember all the details of a formula.

Conclusion # 4: Analogies and propositions play an important role in the monitoring activities of both experts and novices. This finding is consistent with the literature on analogies and propositions. As explicated earlier, studies indicated that outstanding designers rely implicitly or explicitly on first principles in the origination and development of concepts. Analogies are invaluable representations used by designers to resolve functional and structural problems in a design (Cross, 2004; Ullman, 2003). Engineering designers also rely extensively on heuristics when performing analysis on their design solutions. Formulas and heuristics are also important when scientific tests are done to optimize a specific solution.

Conclusion #5: In engineering design, evaluation plays a larger role in the solution space of expert designers, while the novice designers tend to do more planning in the problem space. This conclusion relates to finding number five. The decrease in planning activities and increase in monitoring and evaluation activities as the designers move from the problem space to the solution space were not surprising and is consistent with what Davidson et al. (1995) implied about metacognition in problem-solving. The findings, however, indicate that the engineering students did more planning than the professional engineers. This conflicts with literature on metacognition in problem solving. For example, Davidson et al. stated that "individuals with less expertise in solving a particular problem seem to spend relatively less time in global 'up front' planning for solution, and relatively more time in attempting to implement a solution than do experts" (p. 218). Atman et al. (2007) also found that expert mechanical engineers spent twice as much time in problem scoping activities such as problem definition and gathering information—which are elements of planning. The challenging nature of the design problem and also the training that the engineering students receive in their design classes, which might emphasize detailed planning, might account for why the engineering students spent more time planning than the professional engineers.

It is not surprising that the professional engineers used more monitoring and evaluation in their solution space. In fact, the literature on metacognition indicates that experts excel in these self-regulatory and appraisal skills. These skills are manifested when designers make decisions about alternative solutions and optimize a specific design conceptualization. The time spent in decision making is likely to be related to the time spent generating and evaluating solutions (Radcliffe & Lee, 1989). Experienced engineers were also observed to make preliminary evaluations of their tentative decision, perform final evaluation, balance systems of benefits and tradeoffs, and used guidelines and rule-of-thumb when making decisions (Ahmed, Wallace, & Blessing, 2003; Crismond, 2007).

Recommendations

In evaluating the results of this study a number of recommendations can be made about curriculum development and instruction in engineering education, and engineering design practice in industry. These recommendations should not be viewed in isolation, but as a part of the combined pedagogical and developmental strategies that are influenced by research findings in engineering design, and which are aimed at developing the design skills of engineering students and newly hired engineers. Recommendations are also made for researchers who desire to pursue research in this area.

Recommendations for engineering education curriculum development and instruction. The forgoing conclusions provide some insight into the cognitive processes of novice and expert designers, and from these several recommendations are appropriate for engineering education curriculum and instruction.

The first recommendation relates to the first four conclusions. During conceptual design activities, the tasks in the curriculum that target the solution space; such as generating alternatives, analysis, optimization, and decisions; should be structured so that students are allowed to be exposed to the use of multiple forms of representations. The findings indicate that this is one way in which the experts' design cognition differs from the engineering students—in their balanced use of different mental representations. The content of curriculum and the teaching strategy used should not rely exclusively on engineering science or mathematical formulas, but should also encompass heuristics and incorporate other strategies that develop students' mental models and build not only their analytical, but also their qualitative representations. In fact Jonassen, Strobel, and Lee's (2006) research on the everyday problem solving strategy of engineers, noticed that only a small minority of workplace engineers regularly use mathematical formulas to represent problems. They recommended that teaching in college classrooms should supplement mathematical formulas with alternative qualitative representations. The objective is to build the student's repertoire of a variety of representations that would increase their ability to produce functional descriptions of design solutions, which correlate with high quality designs.

The findings indicated that the professional engineers used more between-domain analogies than within-domain analogies. The engineering students, however, used more within-domain analogies than between-domain analogies. Between-domain analogies are distant in terms of their surface features, but share similar conceptual structure. Between-domain analogies or schema-driven analogies are often associated with creative solutions and experts tend to be more proficient than novices in using them. The ability to look beyond the disparate surface feature of source analogies and the design problems that they target, and identify common conceptual structures that link them together, is not easy, and usually takes years of substantial experience solving different types of design problems. Gentner, Loewenstein, and Thompson (2003) opined that specific instructional intervention; such as accelerated example-based learning; may improve students' ability to solve problems in an expert-like manner. The same principle can be applied in design instruction. Instructions that expose students to a wide variety of designs examples, and which allow students to make active comparison, critique, and evaluation to understand the underlying concepts that make certain designs similar or different, will likely result in the formation of highly structured schemas, thus improving students' ability to make analogical comparisons that goes beyond surface similarities.

The second recommendation relates to the fifth conclusion. While there was similarity in the monitoring and evaluation strategies of the engineering students and professional engineers, the engineers showed evidence of carrying out more evaluation using heuristics and formulas that are based on engineering science principles. Evaluation is recognized as a higher order cognitive skill at which experts excel. Design curriculum and teaching strategies should therefore target the development of these skills. Engineering students in college should be taught how to use both engineering science principles and heuristics (rule of thumb) to frame the strategy they will use in their design and monitor their design conceptualizations. At later stages in the design, activities that challenge students to determine the best alternative solutions through the conducting of scientific tests can also build students evaluative skills. According to Crismond (2007, p. 27), "Students can develop their own guidelines based on tests they conduct by formulating design rules-of-thumb. Design rules-of-thumb can strengthen the link between science and engineering design and amount to intermediate abstractions that link the concrete realities of a particular mechanism and product with relevant concepts and laws from engineering and the natural sciences."

The increased evaluation activities by the professional engineers were evident primarily when they reflected on or reviewed their processes and solutions. Self-monitoring and evaluation are associated with higher levels of design quality (Crismond, 2007). Design curriculum should therefore contain activities that allow students to reflect and critique their own and other's design process and product. For example, students can reflect and critique their own design diaries and portfolios and also the design process and product of other professional designers. Crismond recommended that giving students practice at identifying others' design strategies can make their design-oriented metacognition more accurate and automatic.

Recommendations for engineering practice. The foregoing conclusions give some insight into the probable entry behavior in engineering design of newly hired engineers who just completed their college education. Often, newly hired engineers are socialized into new organization through work groups and mentors who are assigned by their supervisor or manager. In fact, Korte (2009), in a case study of 30 newly hired engineers in a large manufacturing organization, found that the "most satisfying learning experiences reported by new comers resulted from developing high quality mentoring relationships with an experienced coworker" (p. 295). These mentorship relations help new engineers to know what the tasks of the job are and how to do them. Awareness of the tendency of new graduate engineers not to do much evaluation, experienced mentors can help them to develop effective design evaluation strategies. Design team members can also help newly hired engineers to not bias their use of mental representations to any one form, but to use different forms optimally, at various stages of the design process, in order to produce the best solutions allowable by the design constraints and the customer's requirement.

Recommendations for future research. Four recommendations are offered for future research. First, this study shows that there is some relationship between the use of propositions (heuristics and formulas) and metacognition such as monitoring and evaluation. The sample size used however was small, so a study with a larger sample size will provide more generalizable data about the nature of this relationship. Second, experimental studies could also show if there is a difference in the quality of students design process and product when they use any one, or a combination of the three representations—formulas, heuristics, and analogies—in engineering design. Third, studies can be done to determine how the quality and speed of students' design are impacted when students are exposed to specific monitoring and evaluation strategies in their design instructions. Finally, verbal protocol analysis can be used to examine the use of mental representation and metacognition in the problem space and solution space by working design groups of engineering students and professional engineers, as they solve a design problem over an extended period, to determine if similar results are obtained as with single participants.

References

Ahmed, S., Wallace, K. M., & Blessing, L. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design, 14*, 1-11.

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education, 96*(4), 359-379.

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design process. *Journal of Engineering Education*, *87*(2), 121-132.

Ball, L. J., Ormerod, T. C., & Morley, N. J. (2004). Spontaneous analogizing in engineering design: A comparative analysis of experts and novices. *Design Studies*, *25*(5), 495-508. doi:10.1016/j.destud.2004.05.004

Bedard, J., & Chi, M. T. (1992). Expertise. *Current Direction in Psychological Science*, *1*, 135-139. doi: 10.1111/1467-8721.ep10769799

Bereiter, C., & Scardamalia, M. (1987). *The psychology of written composition*. Hillsdale, NJ: Erlbaum.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school* (Expanded ed.). Washington, DC: National Academy Press.

Brewer, F. W. (2003). Mental models. In L. Nadel (Eds.), *Encyclopedia of Cognitive Science* (Vol. 3, pp. 1-6). New York, NY: Nature Publishing Group.

Brophy, S., Klein, S., Portmore, M., & Rogers, C. (2008). Advancing engineering education in P-12 classroom. *Journal of Engineering Education, 97(*3), 369-387.

Brown, A. L. (1978). Knowing when, where, and how to remember: A problem of metacognition. In R. Glaser (Eds.), *Advances in instructional psychology* (Vol. 1, pp. 77–165). Hillsdale, NJ: Erlbaum.

Cardella, M. E., Atman, C. J., Turns, J., & Adams, R. (2008). Students with differing design as freshmen: Case studies on change. *International Journal of Engineering Education, 24*(2), 246-259.

Casakin, H. (2003). Visual analogy as a cognitive strategy in the design process: Expert versus novice performance. In N. Cross & E. Edmonds (Eds.), *Expertise in design*. Sydney, Australia: University of Technology Creativity and Cognition Press.

Casakin, H., & Goldschmidt, G. (1999). Expertise and the use of visual analogy: Implications for design education. *Design Studies*, *20*(2), 153-175. doi:10.1016/S0142-694X(98)00032-5

Chan, L. K. S., & Moore, P. J. (2006). Development of attributional beliefs and strategic knowledge in Years 5 to 9: A longitudinal analysis. *Educational Psychology, 26*(2), 161-185. doi: 10.1080/01443410500344209

Chi, M. T. H., Glaser, R., & Farr, M. J. (1988). *The nature of expertise.* Hillside, NJ: L. Erlbaum Associates.

Chrismond, D. (2007). *Contrasting strategies of beginning and informed designers. One representation of learning progression in engineering design*. Retrieved from http:eres.li.umn.edu/eres/docs/20642/crismond_designstrategy_paper.pdf

Christiaans, H., & Dorst, K. (1992). Cognitive models in industrial design engineering: A protocol study. *Design Theory and Methodology, 42*, 131-140.

Christensen, B., & Schunn, C. D. (2007). The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Memory and Cognition, 35*(1), 29-38.

Christensen, T., & Yasar, S. (2007). Paradigms and protocols in the study of creative collaboration: Implications for research design team process and product. *Proceedings of the International Societies of Design Research: Hong Kong Polytechnic University*. Retrieved from http://www.sd.polyu.edu.hk/ iasdr/proceeding

Cross, N. (2004). Expertise in design: An overview. *Design Studies, 25*(5), 427- 441.

Cross, N. (2002). Creativity cognition in design: Processes of exceptional designers. In T. Hewett & T. Kavanagh (Eds.), *Creativity and cognition* (pp. 14-19). New York, NY: ACM Press.

Daugherty, J., & Mentzer, N. (2008). Analogical reasoning in the engineering design process and technology education applications. *Journal of Technology Education, 19*(2), 7-21.

Davidson, J. E., Deuser, R., & Sternberg, R. J. (1995). The role of metacognition in problem solving. In J. Metcalfe & A. P. Shimamura (Ed.), *Metacognition: Knowing about knowing* (pp. 208-225). Cambridge, MA: MIT Press.

Diaz-Hierera, J. L. (2001, October). Engineering design for software: On defining the software engineering profession (T2D). *Paper presented at the 31st ASEE/IEEE Frontiers in Education conference, Reno, NV.*

Donndelinger, S. J. (2005). Integrating comprehension and metacognitive reading and strategies. In S. E. Israel, C. C. Block, K. L. Bauserman & K. Kinnucan-Welsch (Eds.), *Metacognition in literacy learning: Theory assessment, instruction, and professional development* (pp. 41-59). Mahwah, NJ: Lawrence Erlbaum Associates.

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem-solution. *Design Studies, 22*(5), 425-437. doi:10.1016/S0142-694X(01)00009-6

Dunslosky, J., & Thiede, K. W. (1998). What makes people study more? An evaluation of factors that affect self-paced study. *Acta Psychologica, 98,* 37-56.

Dym, C., Agogino, A., Eris, O., Frey, D., & Leifer, L. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education, 94*(1), 103-120.

Egan, D., & Schwartz, B. (1979). Chunking in recall of symbolic drawing. *Memory and Cognition, 7*(2), 149-159.

Eide, R. A., Jenison, R. D., Mashaw, L. H., & Northup, L. L. (2002). *Introduction to engineering design and problem solving*. Boston, MA: McGraw Hill.

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis* (2nd ed.). Cambridge, MA: MIT Press.

Flavell, J. H. (1978). Metacognitive development. In J. M. Scandura & C. J. Brainerd (Eds), *Structural/process theories of complex human behavior*. Alphen a.d. Rijn, The Netherlands: Sijthoff & Noordhof.

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *American Psychologist, 34*(10), 906-911.

Gall, M., Gall, J., & Borg, W. (2007). *Educational research: An introduction* (3rd ed.). Boston, MA: Pearson Education.

Garner, R. (1987). *Metacognition and reading comprehension*. Norwood, NJ: Ablex Publishing.

Gentner, D., Loewenstein, J., Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(3), 393-408.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *The American Psychologist, 52*, 45-56. doi: 10.1037/0003-066X.52.1.45

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology, 12,* 306-355. doi: 0010-0285/80/030360-50

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15,* 1-38. doi: 0010-0285183/010001

Glaser, R., & Chi, M. T. (1988). Overview. In M. Chi, R. Glaser & M. Farr (Eds.), *The nature of expertise* (pp.15-28). Hillside, NJ: Earlbaum.

Greca, I. M., & Moreira, M. A. (1997). The mental representations: Models, propositions and images used by college physics students regarding the concept of field. *International Journal of Science Education, 19*(6), 711-724. doi: 10.1080/ 0950069970190607

Goel, V., & Pirolli, P. (1989). Motivating the notion of generic design within information process: The design problem space. *Artificial Intelligence Magazine, 10*(1), 19-36.

Hartman, D. K. (1995). Eight readers reading: The intertexual links of proficient readers reading multiple passages. *Reading Research Quarterly, 30*(3), 520-561.

Hayes, J. R. (1989). *The complete problem solver* (2nd ed.). Hillside, NJ: Lawrence Erlbaum Associates.

Hey, J., Linsey, J., Agogino, A. M., & Wood, K. L. (2008). Analogies and metaphors in creative design. *International Journal of Engineering Education, 24*(2), 283-294.

Holyoak, K. J., & Koh, K. (1987). Surface and structural similarity in analogical transfer. *Memory & Cognition*, *15*, 332-340.

Johnson, S. D. (1992a). *Cognitive science and technology education.* Paper presented at the 79th Mississippi Valley Industrial Teacher Education conference, Chicago, IL.

Johnson, S., & Satchewell, R. (1993). The effect of functional flow diagram on apprentice aircraft mechanics' technical system understanding. *Performance Improvement Quarterly*, *6*(4), 73-91.

Jonassen, D. H. (1997). Instructional design model for well-structured and ill-structured problem-solving learning outcomes. *Educational Technology Research and Development, 45*(1), 65-94.

Jonassen, D. H. (2000). Towards a design theory of problem solving. *Educational Technology Research and Development, 48*(4), 63-85. Retrieve from http://www.springerlink.com.proxy2.library.uiuc.edu/content/tnk3716r532x0827/fulltext.pdf

Jonassen, D. H., Strobel, J., & Lee, C. B. (2006). Everyday problem solving in engineering: Lessons for engineering educators. *Journal of Engineering Education, 95*(2), 139-151.

Keane, M. (1987). On retrieving analogue when solving problems. *The Quarterly Journal of Educational Psychology, 39*(1), 29-41.

Kellogg, R. T. (1995). *Cognitive Psychology*. London, England: Sage Publications.

Kincannon, J., Gleber, C., & Kim, J. (1999, February). *The effects of metacognitive training on performance and use of metacognitive skills in self-directed learning situations.* Paper presented at the National Convention of the Association for Educational Communications and Technology, Houston, TX.

Kitchener, K. S. (1983). Cognition, metacognition, and epistemic cognition: A three level model of cognitive processing. *Human Development, 26*, 222-232. doi:10.1159/000272885

Klahr, D. (2000). *Exploring Science: The cognition and development of discovery processes.* Cambridge, MA: The MIT Press.

Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science 12*, 1-55.

Korte, R. F. (2009). How newcomers learn the social norms of an organization: A case study of the socialization of newly hired engineers. *Human Resource Development Quarterly, 20*(3), 285-306. doi: 10.1002/hrdq.20016

Kruger, C., & Cross, N. (2001). Modelling cognitive strategies in creative design. In J. Gero & M. Maher (Eds.), *Computational and cognitive models of creative design*, (pp. 205-226). University of Sydney, Australia: Key Centre of Design.

Lawanto, O. (2007). *Self-appraisal and self-management of cognition and problem difficulty: Relationship and metacognitive changes during an engineering design project.* Unpublished doctoral dissertation. University of Illinois—Urbana-Champaign.

Lesgold, A. (1988). Problem solving. In R. J. Sternberg & E. E. Smith (Eds.), *The psychology of human thought* (pp. 188-213). New York, NY: Cambridge University Press.

Lewis, T. (2008). Creativity in technology education: Providing children with glimpses of their inventive potential. *International Journal of Technology and Design Education*, *19*(3), 255-258.

Lewis, T. (2005). Coming to terms with engineering design as content. *Journal of Technology Education*, *19*(3), 255-258.

Maher, L., Poon, J., & Boulanger, S. (1996). Formalizing design exploration as co-evolution: A combine general approach. In J. S. Gero & F. Sudweeks (Ed.), *Advances in formal design method for CAD*. London, England: Chapman and Hall.

Marzano, R. J., Brandt, R. S., Hughes, C. S., Jones, B. F., Presseisen, B. Z., Rankin, S. C., & Suhor, C. (1988). *Dimensions of thinking: A framework for curriculum and instruction.* Alexandria, VA: Association for Supervision and Curriculum Development.

Meier, J., Veenman, M., & van Hout-Wolters, B. (2006). Metacognitive activities in text-studying and problem-solving: Development of a taxonomy. *Educational Research and Education, 12*(3), 209-237.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (3rd ed.). London, England: Sage Publications.

NCETE. (2008). National Center for Engineering and Technology Education. Retrieved from http://ncete.org/flash/about.php

Needham, D. R., & Begg, I. M. (1991). Problem-oriented training promotes spontaneous analogical transfer: Memory-oriented training promotes memory for training. *Memory and Cognition*, *19*(6) 543–557.

Newel, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice Hall.

O'Neil, H., & Abedi, J. (1996*). Reliability and validity of a state metacognitive inventory: Potential for alternative assessment* (CSE Tech. Rep. No. 469). Los Angeles: University of California, Center for the Study of Evaluation/National Center for Research on Evaluation, Standards, and Student Testing.

Paris, S. G., & Winograd, P. (1990). Metacognition in academic learning and instruction. In B. F. Jones (Ed.), *Dimension of thinking and cognitive instruction* (pp. 15-44). Hillsdale, NJ: Erlbaum.

Paivio, A. (1990). *Mental representations*. New York, NY: Oxford University Press.

Pintrich, P. R., & DeGroot, E. V. (1990). Motivational and self-regulated learning components of classroom academic performance. *Journal of Educational Psychology, 82*(1), 33-40.

Phye, G. D. (1986). Practice and skilled classroom performance. In G. D. Phye & T. Andre (Eds.), *Cognitive classroom learning: Understanding, thinking, and problem solving* (pp.141-168). Orlando, FL: Academic Press.

Practor, R. W., & Dutta, A. (1995). *Skill acquisition and human performance*. Thousand Oaks, CA: Sage Publication.

Radcliffe, D. F., & Lee, T. Y. (1989). Design methods used by undergrad engineering students. *Design Studies, 10*(4), 199-207.

Ravitz, J. (2008). Project–based learning as a catalyst in reforming high schools. Retrieved from http://www.bie.org/files/AERA_PBL_2008.pdf

Romer, A., Leinert, S., & Sachse, P. (2000). External support of problem analysis in design problem solving. *Research in Engineering Design, 12*, 144-151. Retrieved from http://www.springerlink.com.proxy2.library.uiuc.edu/content/blrhc5qn deg6trec/fulltext.pdf

Royer, J. M. (1986). Designing instruction to produce understanding: An approach based on cognitive theory. In G. D. Phye & T. Andre (Eds.), *Cognitive classroom learning, understanding, thinking, and problem solving* (pp. 83-113). London, England: Academic Press, INC.

Schraw, G., & Moshman, D. (1995). Metacognitive theories. *Educational Psychology Review, 7*(4), 351-371.

Ullman, D. G. (2003). *The mechanical design process.* New York, NY: McGraw Hill

Veenman, M. V. J., & Verheij, J. (2003). Technical students' metacognitive skills: Relating general vs. specific metacognitive skills to study success. *Learning and Individual Differences, 13*, 259-272. doi:10.106/S1041-6080(02)00094-8

Veenman, M. V. J., van Hout-Wolters, B., & Afflerbach, P. (2006). Metacognition and learning: Conceptual and methodological considerations. *Metacognition and Learning*, *1*, 3-14.

West, C. K., Farmer, J. A., & Wolff, P. M. (1991). *Instructional design: Implications from cognitive science.* Englewood Cliffs, NJ: Prentice Hall.

Appendix A

Mental Representation Matrices

Len (Junior)

	Mental space			
Mental Representation	Problem space	Overlapping Space	Solution Space	Total
Proposition			2	2
Metaphor		1	1	2
Analogy	2		8	10
Total	2	1	11	14

Vel (Junior)

	Mental space			
Mental Representation	Problem space	Overlapping Space	Solution Space	Total
Proposition		3	1	4
Metaphor				0
Analogy	1	2	3	6
Total	1	5	4	10

Hank (Junior)

	Mental space			
Mental Representation	Problem space	Overlapping Space	Solution Space	Total
Proposition	1		6	7
Metaphor				0
Analogy	2	4	5	11
Total	3	4	11	18

Don (senior)

Mental Representation	Mental space Problem space	Overlapping Space	Solution Space	Total
Proposition	3	2	4	9
Metaphor	1			1
Analogy	5	1	5	11
Total	9	3	9	21

Lina (senior)

Mental Representation	Mental space Problem space	Overlapping Space	Solution Space	Total
Proposition		1	3	4
Metaphor				0
Analogy		2	2	4
Total		3	5	8

Gus (senior)

Mental Representation	Mental space Problem space	Overlapping Space	Solution Space	Total
Proposition				0
Metaphor	1			1
Analogy	1	1	8	10
Total	2	1	8	11

Mac (professional engineer)

Mental Representation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Proposition		1	10	11
Metaphor	1	2		3
Analogy			9	9
Total	1	3	19	23

Ven (Professional engineer)

Mental Representation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Proposition		3	4	7
Metaphor				0
Analogy		5	4	9
Total				16

Ray (professional engineer)

Mental Representation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Proposition			4	4
Metaphor				0
Analogy			10	10
Total			14	14

Lee (expert)

Mental Representation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Proposition			1	1
Metaphor				0
Analogy		2		2
Total		2	1	3

Appendix B

Mental Representation Meta-Matrices

Engineering Students Mental Representation Frequency

	Problem space	Overlapping Space	Solution Space	Total
Proposition	4	6	16	26
Metaphor	2	1	1	4
Analogy	11	10	31	52
Total	17	17	48	82

Professional Engineers Mental Representation Frequency

	Problem space	Overlapping Space	Solution Space	Total
Proposition	0	3	19	22
Metaphor	1	2	0	3
Analogy	0	7	23	30
Total	1	12	42	55

Appendix C

Metacognitive Regulation Matrices

Len (Junior)

		Mental space		
Metacognitive Regulation	Problem space	Overlapping Space	Solution Space	Total
Planning	3	4		7
Monitoring		3	10	13
Evaluation		2	1	3
Total	3	9	11	23

Vel (Junior)

		Mental space		
Metacognitive Regulation	Problem space	Overlapping Space	Solution Space	Total
Planning	3	5		8
Monitoring		11	4	15
Evaluation			1	1
Total	3	16	5	24

Hank (Junior)

		Mental space		
Mental Representation	Problem space	Overlapping Space	Solution Space	Total
Planning	5	1		6
Monitoring	4	4	9	17
Evaluation		2	4	7
Total	9	7	13	30

Don (senior)

Metacognitive Regulation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Planning	9	1	1	11
Monitoring		2	14	16
Evaluation			5	5
Total	9	3	20	32

Lina (senior)

Metacognitive Regulation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Planning	1			1
Monitoring		1	2	3
Evaluation			3	3
Total	1	1	5	7

Gus (senior)

Metacognitive Regulation	Mental space: Problem space	Overlapping Space	Solution Space	Total
Planning	1	2		3
Monitoring		3	3	6
Evaluation		1	2	3
Total	1	6	5	12

Mac (professional Engineer)

Metacognitive Regulation	Problem space	Mental space Overlapping Space	Solution Space	Total
Planning	2	3	2	7
Monitoring		6	14	20
Evaluation			14	14
Total	2	9	30	41

Ven (professional Engineer)

Metacognitive Regulation	Problem space	Mental space Overlapping Space	Solution Space	Total
Planning	1	2	1	4
Monitoring	2	2	14	18
Evaluation		1	15	16
Total	3	5	30	38

Ray (professional engineer)

Metacognitive Regulation	Problem space	Mental space Overlapping Space	Solution Space	Total
Planning	1	1		2
Monitoring		2	13	15
Evaluation		1	6	7
Total	1	4	19	24

Lee (expert)

Metacognitive Regulation	Problem space	Mental space Overlapping Space	Solution Space	Total
Planning	4	1		5
Monitoring			4	4
Evaluation				
Total	4	1	4	9

Appendix D

Metacognitive Regulation Meta-Matrices

Engineering students' Metacognitive Regulation Frequency

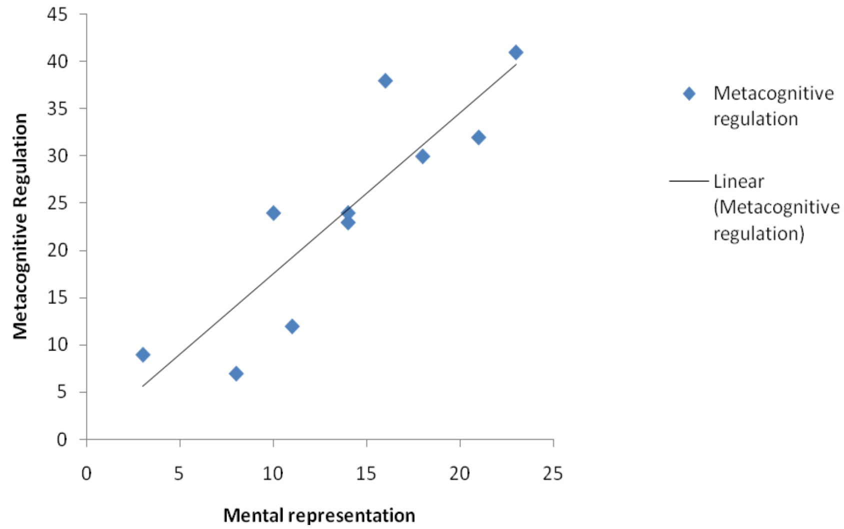
	Problem space	Overlapping Space	Solution Space	Total
Planning	22	13	1	36
Monitoring	4	24	42	70
Evaluation	1	5	16	22
Total	27	42	59	128

Professional engineers' Metacognitive Regulation Frequency

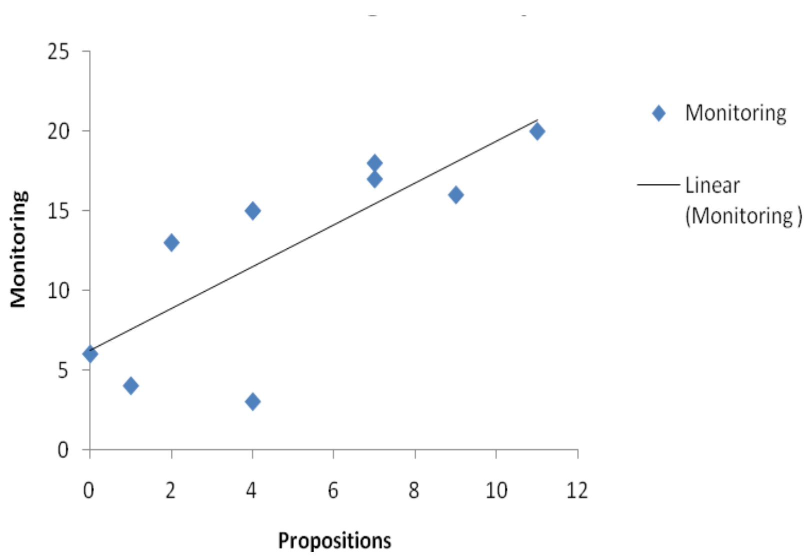
	Problem space	Overlapping Space	Solution Space	Total
Planning	8	7	3	18
Monitoring	2	10	45	57
Evaluation		2	35	37
Total	10	19	83	112

Appendix E

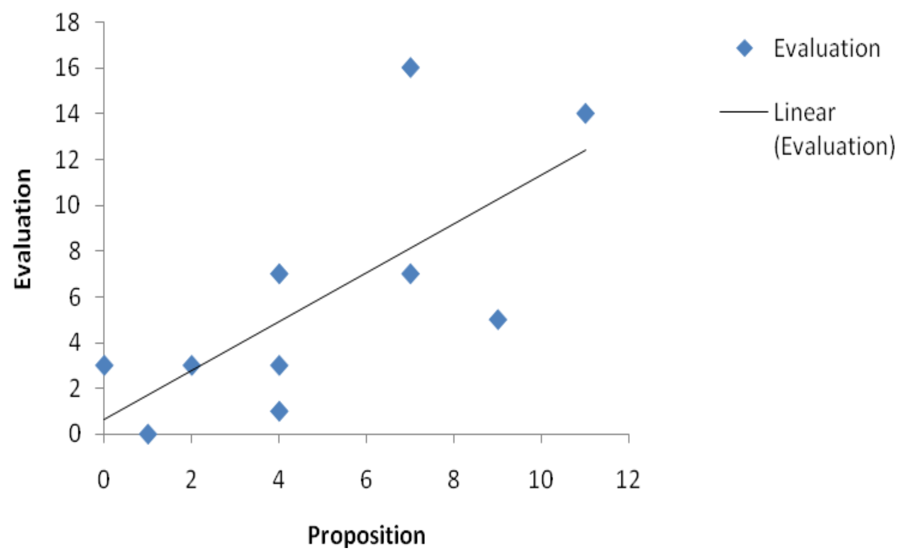
Spearman Correlations and Scatterplot Diagrams



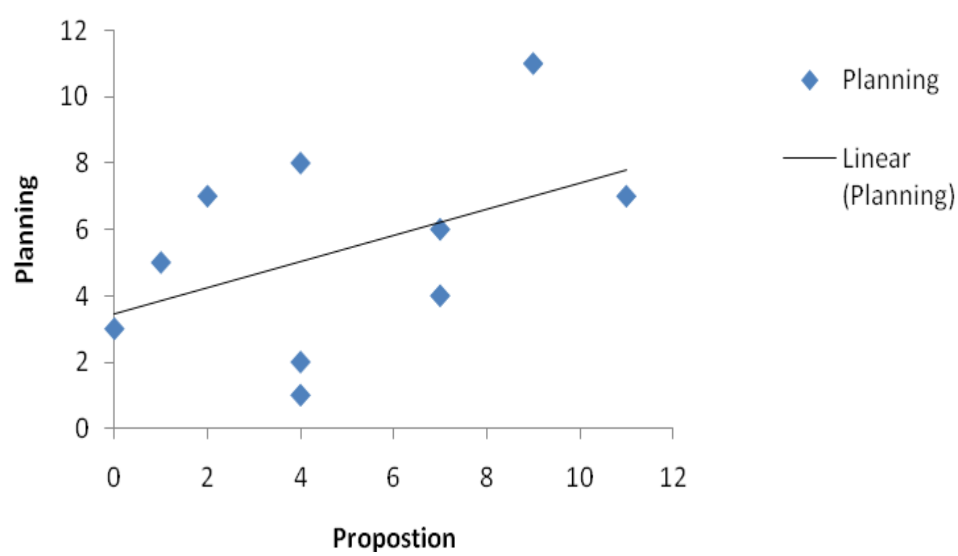
Correlation between mental representation and metacognitive regulation, ρ (10) = 0.87



Correlation between proposition and monitoring, ρ (10) = 0.82

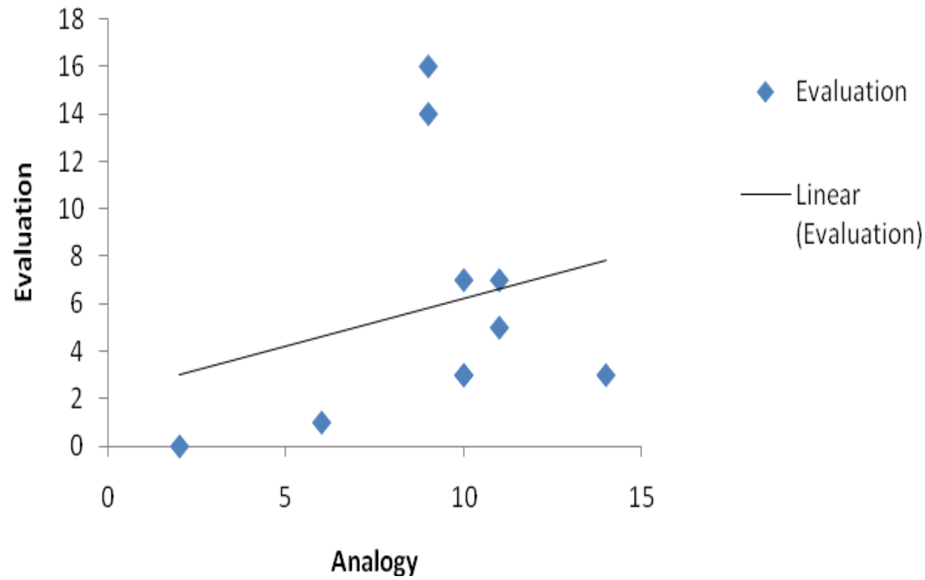


Correlation between proposition and evaluation, ρ (10) = 0.71

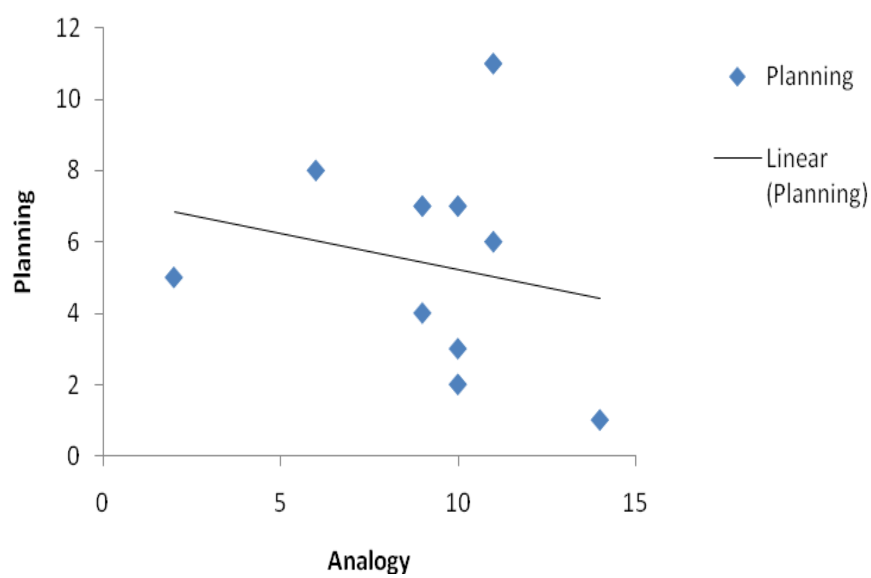


Correlation between proposition and planning, ρ (10) = 0.46

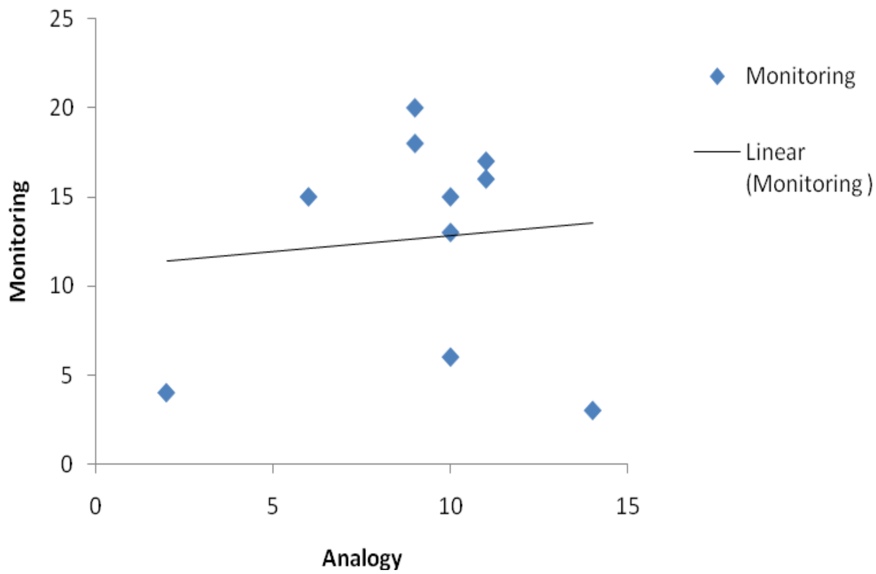
-



Correlation between analogy and evaluation, ρ (10) = 0.24



Correlation between analogy and planning, ρ (10) = -0.24



Correlation between analogy and monitoring, ρ (10) = 0.09